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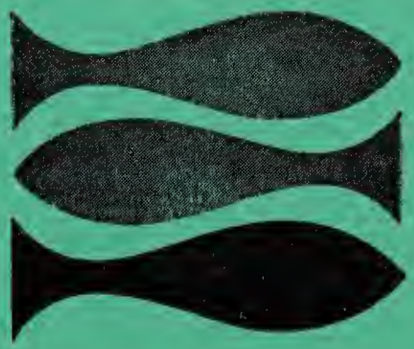

INTERNATIONAL NORTH PACIFIC FISHERIES COMMISSION

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BULLETIN NUMBER 13

SALMON OF THE NORTH PACIFIC OCEAN
PART II

REVIEW OF OCEANOGRAPHY OF THE SUBARCTIC PACIFIC REGION

by A.J. Dodimead, F. Favorite and T. Hirano

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VANCOUVER, CANADA, 1963

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INTERNATIONAL NORTH PACIFIC FISHERIES COMMISSION

Established by Convention between Canada, Japan and the United States for the Conservation of the Fisheries Resources of the North Pacific Ocean

BULLETIN NUMBER 13

SALMON OF THE NORTH PACIFIC OCEAN
PART II

Review of Oceanography of the Subarctic Pacific Region

by A.J. Dodimead, F. Favorite and T. Hirano

OFFICES: 6640 Northwest Marine Drive
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PREFACE

In 1955 the International North Pacific Fisheries Commission began an extensive program of scientific research on the high seas of the North Pacific Ocean. The program, which continues to the present time, is executed by research organizations of the countries which established the Commission—Canada, Japan and the United States. Principal attention is directed to salmon, genus *Oncorhynchus*, as required by the Protocol to the North Pacific Convention.

This bulletin contains the first jointly-written report of research results to be published by the Commission. It describes the oceanography of the Subarctic Pacific Region, in which salmon spend the marine portion of their existence. The bulletin forms Part II of a comprehensive report on North Pacific salmon, which is being prepared and published by the Commission. Part I of the report appears in Bulletin 12 of the Commission; Part I presents historical statistics of salmon catches and contains an introduction describing the nine separate parts which are planned for the comprehensive report.

Prior to their publication in this bulletin series, research reports have first received the approval of three editorial referees, following which they have been approved for publication by the members of the Commission. At the present time the editorial referees are Messrs. Tasuku Hanaoka for Japan, Donald L. McKernan for the United States and A.W.H. Needler for Canada. Bulletins of the Commission are published separately in English and Japanese. The original language of each paper is indicated and accuracy of translation is the responsibility of the Secretariat.

The various parts of the report on salmon of the North Pacific Ocean may be published out of order; each part will be published as it is completed and receives the approval of the referees and the Commission.

ROY I. JACKSON,
Executive Director.

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REVIEW OF OCEANOGRAPHY OF THE SUBARCTIC PACIFIC REGION

by
A. J. Dodimead, Fisheries Research Board of Canada, Pacific Oceanographic Group
Nanaimo, British Columbia, Canada
F. Favorite, Bureau of Commercial Fisheries, Biological Laboratory, Seattle, Washington
United States of America
T. Hirano, Tokai Regional Fisheries Research Laboratory, Fisheries Agency
Tokyo, Japan
October 1, 1962

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FOREWORD

The International North Pacific Fisheries Commission (INPFC), whose three member nations are

Canada, Japan and the United States of America, was established under the International Convention for the High Seas Fisheries of the North Pacific Ocean in 1953 for the purpose of promoting and coordinating scientific studies necessary to ascertain the conservation measures required to secure the maximum sustained productivity of fisheries of common interest to the members.

One of the immediate tasks assigned to the Commission was " as expeditiously as practical, investigate the waters of the Convention area to determine if there are areas in which salmon (genus *Oncorhynchus*) originating in the rivers of Canada and of the United States of America intermingle with salmon originating in the rivers of Asia. If such areas are found the Commission shall conduct suitable studies to determine a line or lines which best divide salmon of Asiatic origin and salmon of Canadian and United States of America origin " (fully stated in the Protocol of the Convention).

Realizing the importance of the environment, the Standing Committee on Biology and Research recommended oceanography as a possible aid to an understanding of salmon distribution and their movements. Briefly, the basic oceanographic requirements or problems were to determine the characteristics of the environment or region in which salmon are known to live; relate the extent of the environment to the pattern of currents and water structure; observe and recognize seasonal variations in this environment; and determine mechanisms that could account for the observed conditions and factors that cause changes. Presumably, a thorough understanding of these would ultimately lead to a prediction of the marine environment from limited or special oceanographic observations.

At the beginning of the INPFC investigations, national interests permitted an easy division of effort to solve the above problems. Both in operational and research work, the division of effort was made into three broad areas within the Subarctic Pacific Region; western Subarctic (Japan), central Subarctic (United States of America) and eastern Subarctic (Canada). No rigid boundaries were imposed and, in fact, considerable overlap sometimes occurred. This was necessary in order to completely define conditions in these specific areas. Then too, it became evident that a consideration of the whole Region was essential in order to have an appreciation of the continuity or lack of continuity of properties throughout the Region. This approach was developed but was only possible because the data were processed quickly and exchanged freely, often in prepublished form. This quick exchange of data, from one to eight months after completion of a cruise, was a major accomplishment, especially during the early INPFC work when modern equipment such as salinometers and data processing machines did not exist or were not readily available.

Oceanographic observations at sea were generally made in a similar manner by the several agencies, but the analyses of data often proceeded in different directions. This is understandable due to the three-dimensional aspects of the ocean, and the many methods available for the presentation of data. As a result of the different but logical approaches by various authors, it was sometimes difficult to compare particular boundaries or identifying characteristics of the water masses and their movements.

From investigations under the research programs of the INPFC and other agencies, considerable knowledge of the oceanographic features, their seasonal and yearly variations, and mechanisms in the three broad areas and, finally, in the whole Region was accumulated.

In this report, fragmentary information from research conducted prior to the commencement of the INPFC has been summarized. This information and the knowledge obtained from research conducted by the Commission has been synthesized into a presentation of the structure of the water within the Subarctic Pacific Region and a discussion of some of the mechanisms and processes that establish or alter the structure. The dominant features of the structure are used to show the distribution of properties during the years 1955 through 1959. From these distributions. specific domains have been identified, the extent and position of which denote the major changes of conditions during the years considered.

I. SUBARCTIC PACIFIC REGION

There have been many studies in which various methods and parameters have been used to define the geographical extent of what is commonly known as the Subarctic Pacific Region. The purpose here is to review some of these studies, and to arrive at some distinct oceanographic feature or parameter which is easily recognized and will adequately define the southern limit of this Region throughout the North Pacific.

Sverdrup *et al.* (1942), using temperature-salinity (T-S) diagrams, defined a Subarctic Water mass " which is characterized in about lat. 50°N. by an average temperature between 2°C. and 4°C. and by a salinity which at the surface may be as low as 32.00‰ but increases to approximately 34.00‰ at a depth of a few hundred metres and below that depth increases

slowly to about 34.65‰ at the bottom ". They suggested that this water mass occurred only north of lat. 45°N., but generalized the definition to include water approaching the characteristics of Eastern Pacific Water. Figure 1 shows representative T-S curves of these two water masses.

Fleming (1955) in his review and bibliography of the northern Pacific identified regions and zones which were based principally on general oceanographic characteristics and flow of the surface waters. Although specific regions and zones were delineated (Fig. 2) and are coincident with some of the domains identified in this report, the boundaries presented were not specifically defined.

In the western part of the North Pacific, off the coast of Japan, considerable effort has been directed to studies of the narrow frontal zone at the confluence of Oyashio (cold) and Kuroshio (warm) systems (Uda, 1935, 1938, 1949, 1951, 1955; Ichiye, 1955; Kawaii, 1955; Watanabe, 1955; Fukuoka, 1955; Masuzawa, 1954, 1955a, b, 1956, 1957). As a result of these investigations various terms originated; Oyashio Front, Kuroshio Front, Polar Front, Polar Frontal Zone and Subarctic convergence. Many parameters were used to distinguish these systems and to show their geographical variations. For example, Uda (1935) identified the Oyashio system, which he called Subarctic Water, by the presence of a dichothermal temperature (minimum temperature at depth). Others used the depth of particular isotherms (Masuzawa, 1955b) or a surface isotherm, 15°C. (Fukuoka, 1955), to define water masses or regions.

In the central North Pacific southward of the Aleutian Islands, Favorite and Hanavan (1960), utilizing temperature-salinity and oxygen-salinity curves and water structure, defined Subarctic, Transition and Central Pacific boundaries.

Tully and Dodimead (1957), utilizing data in the northeast Pacific, identified Subarctic and Subtropic Waters. They showed that the principal differences were in the properties and structure of the upper layers. Those in the deep waters, within small limits, were similar through the Subtropic and Subarctic Regions of the northern Pacific. Dodimead (1961a), utilizing this concept of structure, defined Subtropic, Transition and Subarctic Waters from the salinity structure in data from all parts of the northern Pacific. In Subarctic Water, the salinity structure had a distinct halocline (left curve, Fig. 1). In Transition Water, the halocline was not so distinct and the structure below the halocline contained a salinity minimum. In Subtropic Water no halocline was present and the resulting T-S curve is similar to that of Eastern Pacific Water (right curve, Fig. 1). These structures are shown and discussed in Section IV, A.

In all these studies, most of the definitions have specified boundaries that are nearly coincident in the ocean, within the limitations of the data, and are probably equally applicable to define the limits of regions. However, not all the methods have been applied from shore to shore across the Pacific, nor are all the parameters easily identified beyond the areas of original applications.

A feature that seems to persist across the North Pacific in summer is an anomalous isohaline structure which occurs, in the oceanic area, beyond coastal waters, at about lat. 42°N. It is identified by the almost vertical isohaline of 34.0‰ which extends from the surface to a depth of about 200 to 400 metres. The feature becomes less distinct in the eastern North Paeific where more dilute surface waters are encountered, but below these waters the structure can be identified. This structure is apparent in all meridional sections as shown along long. 155°E., 175°E. and 160°W. for summer 1958 (Fig. 3). Recently Favorite *et al.* (1962) have shown that this feature of structure exists in the central North Pacific (along long. 175°W.) during winter at about the same latitude.

The isohaline structure, denoted by the 34.0‰ isohaline, is considered to be a boundary separating two distinct Regions, Subarctic and Subtropic. Using this interpretation, the previously discussed Transition Water is considered to be part of the Subarctic water mass. The position of this boundary is nearly coincident with the position where precipitation equals evaporation (Fig. 6) (Jacobs, 1951). These processes along with differential local heating have produced water structures that have distinct characteristics to the northward and southward of approximately lat. 42°N.

North of the boundary, in the Subarctic Region, the salinity is a minimum at the surface and increases with depth. The water column is characterized by a permanent halocline between approximately 100 and 200 metres depth above which a thermocline develops in summer and vanishes in winter. Thus, the temperature structure only contributes to the stability of the water column in summer, while in winter stability of the water column is entirely dependent upon the salinity gradient (halocline).

South of the boundary, in the Subtropic Region, the salinity is a maximum at the surface and decreases to a distinct minimum below 500 metres depth, but the water column is stable. The salinity at the surface is

a maximum due to excess evaporation, and the stability of the water column depends on the temperature structure. The magnitude and depth of the thermocline varies throughout the year, but it does not vanish.

It is possible that changes in wind stress and transports could cause the position of the boundary to meander. Evidence from data collected in 1955, 1958 and 1962 indicates that its position is relatively constant (between lat. 40°N. and 42°N.) in the central North Pacific. The location of the boundary shown in Figure 3 is sufficiently representative for our purposes. This boundary is used consistently throughout this paper and it is considered to be the southern limit of salmon.

II. GEOGRAPHY AND CLIMATE

Figure 4 shows the Subarctic Region as defined in this paper and all geographical terms used.

A. Bathymetry

Figure 5, adapted from the NORPAC Atlas (Oceanic Observations of the Pacific: 1955, 1960a), shows the general bathymetry (in metres) of the northern Pacific[1]. The greatest depths, those exceeding 4000 metres, are found in the deep trenches south of the Aleutian Islands and east of the Kuril Islands. A substantial part of the Region (excluding Bering and Okhotsk Seas) consists essentially of a broad abyssal plain more than 4000 metres in depth, with numerous submarine mountains (seamounts) which rise to within about 700 metres of the surface. The greatest number of these are present in the Gulf of Alaska.

The Aleutian Islands, and the shallow passages through them, limit the exchange of water between the Pacific and Bering Sea. Only Amchitka Pass (long. 179°W.) is deep enough to allow exchange of waters at depths of 1000 metres. Greater depths occur at the end of the Aleutian ridge between the Near and Komandorski Islands.

Bering Strait, 31 miles wide and having a maximum depth of 90 metres, provides a limited access for the exchange of shallow waters between the Bering Sea and the Polar Basin.

Along the Kuril Island chain only two passages exceed 1000 metres depth. Thus, the exchange of waters between the Okhotsk Sea and Pacific Ocean is restricted.

The seaward extent of the continental shelf areas is usually denoted by the 200 metre contour line. Generally there is an abrupt slope at the outer edge of the continental shelf. As a result the 200 metre and 1000 metre contour lines lie very close to one another in this small-scale chart. Therefore, the seaward extent of the continental shelf areas can be roughly denoted by the 1000 metre contour line.

The continental shelf has its widest expanse in the eastern and northern Bering Sea. This area is extremely shallow, possessing average depths of about 60 metres. Also, depths of less than 130 metres are found in an anomalous ridge extending in a northwest direction north of the Aleutian Islands at long. 180°. In the Okhotsk Sea the continental shelf is relatively extensive, and only in the southeastern portion do depths exceed 2000 metres.

B. Climatology

1. *Precipitation.* Jacobs (1951) has shown the net difference between precipitation and evaporation in the North Pacific Ocean. The mean values in winter, in summer, and throughout the year are shown in Figure 6. North of about lat. 40°N. precipitation exceeds evaporation, and southward evaporation predominates (bottom plate, Fig. 6). As noted in the previous section, the boundary where precipitation equals evaporation generally coincides with the boundary between the Subarctic and Subtropic Regions; thus, the Subarctic is a region of net dilution.

2. *Winds.* The mean sea level pressure and prevailing winds during winter (December–March) are shown in Figure 7. In general, the Subarctic is under the influence of a barometric low pressure cell (Aleutian Low) centered in the Bering Sea near the Aleutian Islands. Coincident with this, two high pressure cells (Siberian and North American Arctic High) occur. Under the influence of this barometric pressure distribution, the predominant winds in winter are generally westerly; they blow from the northwest in the western part of the Region, gradually backing through southwest on the eastern side. In the northern part of the Gulf of Alaska, easterly winds prevail.

The corresponding charts of pressure and wind distributions for summer (June–August) are shown in Figure 8. In early summer, the Aleutian Low becomes much less intense and the North Pacific High, centered between about lat. 30°N. and 40°N., becomes predominant. The prevailing westerlies of the winter months are then replaced by predominantly south or southwest winds. These warm southerly winds cause extensive "advection" fogs during passage over the

[1] Recently the U.S. Hydrographic Office has published an excellent series of charts of the depths of the World's oceans of which charts H. O. Misc. 15254–5 and 6 show the bathymetry of the North Pacific Ocean.

cold waters near Kamchatka and the Aleutian Islands. On the eastern side of the Subarctic (near the Canadian and U.S. coasts) the prevailing summer winds blow from the northwest. Generally light, variable winds occur in the Gulf of Alaska at this time.

Recently, Fofonoff (1960 a, b, c, d, e; 1961) has presented the monthly and annual mean pressure distributions for the years 1955 through 1960. These data reflect the marked variations in the strength and extent of the pressure distributions that occurred during this period. The annual mean sea level pressure distributions for the period of this report, 1955 through 1959, are presented in Figure 9.

3. *Sea ice.* In the northern Bering Sea, ice usually forms in October and spreads rapidly southward; the maximum extent usually occurs in February of each year (Fig. 4). During the winter, ice is present throughout the northern half of the Bering Sea and covers the entire Okhotsk Sea. By July, it is found only in the Gulf of Anadyr and in Bering Strait. In July and August, all ice disappears in these areas and open water is present northward of Bering Strait. The U.S. Hydrographic Office has periodically issued reports of ice conditions in the Arctic which include monthly conditions in the eastern and northern Bering Sea.

4. *Incident energy, cloud cover and insolation.* Figure 10 (Tully and Dodimead, 1957) shows the annual cycle of incident energy (gram cal/cm^2/day), assuming no cloud cover, from lat. 35°N. to 60°N. During summer, between lat. 40°N. and 60°N., the incident energy is nearly constant; a gradient develops in autumn, reaches a maximum in winter, and degenerates in spring. Mean values for summer (June–August) and winter (December–February) are also shown in the diagram and range from about 800 to 900 and from 100 to 400, respectively.

Cloud cover absorbs 7.1% of the incident energy for every tenth of the sky obscured. Applying this correction to the average cloud cover during winter and summer, the incident energy at the sea surface for these periods has been computed (Fig. 11). The resulting distributions of energy correspond closely with the distributions of winter and summer surface isotherms.

5. *Sea surface temperature.* A number of sea surface temperature charts, generally compiled from ships' records, are available for various periods. The Japanese Meteorological Agency publishes 10-day reports of sea surface temperatures between lat. 10°N. and 50°N. and west of long. 180°. Since 1957 the U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries Biological Laboratory, San Diego, California (originally published by the Bureau of Commercial Fisheries Biological Laboratory, Honolulu, Hawaii), has been publishing monthly sea surface temperature charts of the North Pacific east of long. 180°. These publications also compare current monthly data to those of the same period in the previous year, and to a long term mean. Recently, a Canadian Oceanographic Information Service (Giovando, 1962) has been established in Esquimalt, B. C. This Service, in addition to publishing weekly sea surface temperature data in the eastern Subarctic Region, publishes other weekly charts such as depth of the seasonal thermocline, magnitude of the thermocline and temperature at the bottom of the thermocline, from daily series of bathythermograph data radioed to the Information Centre.

The Bureau of Commercial Fisheries Biological Laboratory, Stanford, California, has commenced issuing average monthly charts of the northern Pacific which utilize all available data and in which questionable data have been eliminated or corrected. Charts of average monthly sea surface temperatures (°C.) during the year 1956 are produced here to show the monthly ranges of temperature in the Subarctic (Fig. 12 a, b, c, d) (Saur and Eber, 1962). The configuration of the isotherms is generally similar for each month. The waters are coldest in late winter at the end of the cooling season (February and March) and warmest in late summer, at the end of the heating season (August and September). Near the southern limit of the Subarctic a marked north-south gradient persists which is generally called the Polar Front. The annual range over most of the Region is of the order of 6°C. to 9°C. The corresponding charts from other years show the same features; however, the absolute values vary in some localities.

III. HISTORY OF OCEANOGRAPHIC INVESTIGATIONS

The International North Pacific Fisheries Commission was formed in 1953, but it was not until 1955 that any major oceanographic program could be initiated in the Subarctic Pacific Region. Although that year's program was a result of expeditions organized by the NORPAC Committee, oceanographic programs during the following years were maintained and expanded in keeping with the increased exploratory fishing, tagging and research studies conducted to determine the oceanic distribution of salmon. For this review it is convenient to divide the oceanographic investigations and research works concerning the Subarctic into two periods; prior to 1955, and since 1955. The

important sources of data and reference material prior to 1955 are summarized and some of the research works that deal with water structure (characteristics of properties with depth) and circulation are briefly reviewed. Then, a brief outline of the scope and the purpose of the investigations since 1955 is presented, and the data sources and occanographic coverage during 1955 through 1959 are shown. It has been primarily these data that have made it possible to deduce the features of structurcs, mechanisms and domains in the Subarctic Region.

A. Investigations Prior to 1955

Bibliographies of oceanographic cruises and research works during this period have been compiled by various authors and agencies. An early listing of oceanographic data was given by Vaughan (1937). Grier (1941) compiled the important papers dealing with oceanographic and biological studies in the North Pacific to 1938. Following this the U. S. Navy Hydrographic Office (1953) compiled references dealing with "Physical Oceanography of the Western Pacific Ocean". The Japan Agricultural Technical Association (1954) published available data and cruise plans in the northern Pacific Ocean (north of lat. 40°N.) by years for the period 1887–1954. Love (1956) listed the available oceanographic data, primarily that collected between 1916 and 1954, in the portion of the North Pacific Ocean extending from the west coast of North America to long. 150°W. between lat. 20°N. and 50°N.; and Saur (1958), using much the same format, listed meteorological and oceanographic reports of time-series data.

Recently Scripps Institution of Oceanography has been compiling data from the Pacific Ocean. These data are being published by the University of California Press in "Oceanic Observations of the Pacific". To date, the data from the pre-1949 period, 1949 and 1950 have been published (Scripps Institution of Oceanography, 1961, 1957, 1960).

Reports available for this pre-1955 period show that the cruises and subsequent studies were confined to relatively small portions of the Subarctic; e.g., in portions of the Bering Sea, Gulf of Alaska and off the northern Japanese islands. The far-ranging expeditions usually traversed large areas by single lines of oceanographic stations. As a result, detailed studies of the Subarctic were confined to relatively small areas in the Region. Surface temperature conditions and surface drift compiled from ships' records such as those published by Schott (1935); U.S. Department of Agriculture (1938) and the U.S. Hydrographic Office (1944a, b, and 1947) and the Pilot Charts (U.S. Hydrographic Office) were informative but of limited use because they represented average conditions and only showed gross features of properties at the surface. A synoptic picture of the oceanographic properties at depth across the Pacific was not available.

Of the few publications during this period which relate to the entire Subarctic, the most outstanding is that by Sverdrup *et al.* (1942) who reviewed most of the data and research work prior to 1940. They defined specific water masses (as identified by T-S relationships), current systems and transports. In a review of the other investigations, it is convenient to divide the Region into four parts—(1) Bering Sea, (2) Western Subarctic, (3) Central Subarctic (south of the Aleutian Islands) and (4) Eastern Subarctic. These areas are shown in Figure 13, which also shows the major current systems recognized prior to 1955.

1. *Bering Sea.* The first work of interest is that of Ratmanoff (1937). He showed that most of the waters from the Pacific entered the Bering Sea between the Komandorski and Near Islands, and flowed in a northeastward direction through the Bering Sea. A large part of the western edge of this stream eddied back toward Kamchatka forming a counterclockwise gyre and produced a south-flowing current along the shore (see Fig. 14). In the smaller passes between the Aleutian Islands, a northward movement of water was reported surging to the westward in the Bering Sea. This flow was believed to be part of a large clockwise eddy characteristic of the southern portion of the Bering Sea.

Following this work, Barnes and Thompson (1938) reported on the observations made during the years 1933 and 1934 from U.S.S. *Gannet* and U.S. C.G.S. *Chelan.* They noted that surface waters in the Pacific along the southern side of the Aleutian Islands, and at a distance of 40 miles offshore, moved northward with velocities sometimes exceeding 0.3 knots (7 miles/day) and that in some cases this northward flow was accompanied by a slight eastward component. The greater quantity of water apparently flowed north into the deeper passes west of Tanaga Island (long. 178°W.). Water in Bering Sea just north of the Islands flowed toward the east and north, with maximum velocities of about 0.1 to 0.2 knots (2.5 to 5 miles/day). Subsurface currents were similar in direction to the surface currents, but in general, velocities decreased with depth and became negligible or small at a depth of 1000 metres. Goodman *et al.* (1942) summarized the circulation from these earlier works (Fig. 14).

During the years 1938 through 1941, oceanographic

observations were made from the U.S. C.G.T. *Redwing* in the eastern Bering Sea and Bristol Bay (Favorite and Pederson, 1959, and Favorite *et al.*, 1961). A summary of the data is presented in Appendix I.

LaFond and Pritchard (1952) reporting on the results of the 1947 cruise of the U.S.S. *Nereus* in the eastern Bering and Chukchi Seas concluded that southern Bering Sea water flowed northward and was modified by water from the rivers along the Alaska coast and from intrusions of cold high-salinity water from the western Bering Sea. This mixture of water flowed northward through Bering Strait, principally at the surface on the eastern side.

During July and August 1949, United States and Canadian oceanographers participated in what can be considered a multiple ship survey in Bering and Chukchi Seas (Saur *et al.*, 1952; 1955). The surface circulation, computed from the 500 metres reference level (Fig. 15) showed the presence of a counterclockwise circulation in the southern Bering Sea, opposite to that presented by Ratmanoff (1937) or Goodman *et al.* (1942). The temperature minimum that existed at 100 to 150 metres depth was attributed to cooling and convection, and sluggish southeastward advection of cold water across the Bering Sea. Thus, they questioned the existence of the pronounced northeastward current in the central Bering Sea indicated in Figure 14.

Mishima and Nishizawa (1955) reporting on conditions in the southern Bering Sea from results of the 1953 and 1954 cruises of the *Oshoro Maru* also showed stratification of the water column at most stations, a subsurface layer of cold water and low salinity at 100 metres depth and a deeper layer of maximum temperatures at 300 metres. They also suggested that the cold water layer originated near the Asian coast of the Bering Sea and spread over the deeper water of density intruding from the Pacific.

Winter and spring data from the oceanographic surveys in the eastern Bering Sea during 1955 (U.S. Navy Hydrographic Office, 1958) conducted aboard the U.S. C.G.S. *Northwind* and U.S.S. *Burton Island* provided both representative bathythermograph traces and station data. Surface temperatures ranged from −1.85°C. in the ice pack to 3.4°C. in the open water. Further, the water on the shelf under the ice was generally isothermal at about −1.6°C. and isohaline with values between 31.8 and 32.4‰.

2. *Western Subarctic.* With the exception of oceanographic cruises aboard the *Carnegie* in 1929 and *Baird* in 1953, all data collected in the western Subarctic have come from Japanese and Russian cruises.

Prior to 1941, Japanese research ships such as *Unyo Maru*, *Shunkotsu Maru*, *Hakuho Maru*, *Soyo Maru* and *Tankai Maru*, were engaged in oceanographic surveys in relation to fisheries. More detailed observations over a more extensive area were made aboard former Japanese naval vessels, such as *Manshu*, *Komahashi*, *Itsukushima*, *Otomari* and *Ryofu Maru*. Data from most of these cruises were not easily accessible until tabulated and published by the Japanese Agricultural Technical Association (1954).

The most intensive oceanographic work during this period was confined to the area off the coast of Japan, particularly at the confluence of the Oyashio and Kuroshio systems. Uda (1959) has presented a syllabus in which most of these early reports are summarized.

Shigematsu (1933), using data collected aboard the *Unyo Maru* and *Manshu* in 1916 and 1917, computed surface currents in the Okhotsk Sea using 400 decibars as a reference level. He reported a southward flow in the central part of the Sea; near the Kuril Islands the flow divided, part turned northward, and the rest flowed into the Pacific contributing to the Oyashio Current. Uda (1934) proposed that water between 40 and 200 metres depth, having temperatures between 0°C. and 0.5°C. and salinities between 32.3 and 33.0‰, originated in the northern part of the Sea and moved southward along the east coast of Sakhalin Island.

In other reports Uda (1935, 1938) pointed out the existence of this cold water layer in the western Subarctic. He discussed the dichothermal (subsurfaee minimum temperature) and mesothermal (subsurface maximum temperature) layers and suggested a close relationship between the dichothermal layer and the low-salinity water underlying the Kuroshio.

Kishindo (1940 a), utilizing potential temperatures (temperature that a water sample would have if raised adiabatically to the sea surface), concluded that water below 2000 metres in the Okhotsk Sea originated from the Pacific side of the Kuril Islands. He also presented vertieal sections of properties through the Pacific from lat. 56°N. to 72°S. (Kishindo, 1940 b). He reported that the water between 2000 and 3000 metres flowed to the southward and below 4000 metres northward and concluded that the deep water originated in the Antarctic Ocean and not in the Okhotsk Sea.

Later Kajiura (1949) utilizing observations made near the Kuril Islands in summer 1942 aboard the *Ryofu Maru* reported that the near-surface water flowed into the Okhotsk Sea through the northern Kuril

Island passes and out through the central passes. He suggested that the currents were generally weak and were influenced by the prevailing winds.

The first extensive work published in the postwar period was by Saito (1952). Presenting a theoretical analysis of lateral and vertical diffusion between water masses, he discussed the use of T-S curves and identified northern and southern upper water; northern and subpolar intermediate water; deep and bottom water. In most instances these water masses were further subdivided. He also discussed the distribution of properties and extent of water masses off the east coast of Japan during August 1943 and April 1945; and suggested that the surface water in the Bering Sea appeared to be isolated from the surface water in the Oyashio system, but that the intermediate water of the Oyashio was formed by a mixture of intermediate water from the Bering Sea, Okhotsk Sea and the area near the Kamchatka Peninsula.

Since the reopening of the high-seas fisheries in 1952, the *Tenyo Maru* and *Oshoro Maru* have been engaged in oceanographic surveys. Watanabe (1954) reported the results of observations from the *Tenyo Maru* in 1952 and 1954, and discussed the short period variations of surface temperatures. He suggested that fog formation in the region was an important factor in influencing oceanographic conditions during summer.

Hirano (1957a, b) using data collected during 1954 aboard *Tenyo Maru* identified a number of water masses and temperature structures as shown in Figure 16 which provided considerable information concerning water masses and the circulation in this part of the Region.

Since 1955, many other reports have been published utilizing data collected prior to 1955. In reports such as Uda (1955), Hirano (1958, 1961), Koto and Fujii (1958), Sugiura (1957) and Kitano (1958), accounts of oceanographic conditions were presented. Briefly summarized, the reports showed that along the southern side of the Aleutian Islands there was a westward current which branched into the Bering Sea through the many inter-island passages; and furthermore, there was a counterclockwise gyre of Subarctic water centered in the vicinity of lat. 50°N., long. 165°E.

3. *Central Subarctic.* The scarcity of reports concerning this area indicates that it had either been neglected or was inaccessible with the existing ships. The work of Goodman *et al.* (1942) has been discussed. Barnes and Thompson (1938) reporting on oceanographic sections near Adak and Tanaga Islands noted that the water in the Bering Sea to a depth of 400 metres was colder, and from 800 to 3000 metres was warmer, than in the Pacific. Oxygen concentrations in the Bering Sea at the surface and at depths of 150 to 800 metres were greater and below 1000 metres were less than in the Pacific. Concentrations in the minimum oxygen zone were similar in both areas but more than twice as large as minimum concentrations found near the Washington coast in 1933. However, stations in the Aleutian area extended only 50 miles offshore and represent coastal rather than oceanic conditions.

There have been isolated Japanese cruises in the central Subarctic as far back as 1908, but most of the reports of these cruises deal with conditions in the western Subarctic, and have been discussed. However, in 1952, in conjunction with offshore fishing, Japan resumed oceanographic investigations in the central Subarctic. Noting limitations of the data because of the relatively few oceanographic stations, Mishima and Nishizawa (1955) discussed oceanographic conditions southward of the Aleutian Islands during 1953 and 1954. They reported warm water of low salinity flowing westward along the southern side of the Aleutians which, although gradually dissipated by losses into the Bering Sea, extended as far west as long. 165°E. before being completely dissipated. South of this warm water a narrow tongue of abnormally cold water, believed to originate in the Gulf of Anadyr, flowed eastward. These movements were based on the geostrophic currents shown in Figure 17.

4. *Eastern Subarctic.* Early work in this area was undertaken by the International Fisheries Commission to ascertain the nature, direction and velocity of the currents in the Gulf of Alaska as an aid in the biological studies of the halibut (McEwen *et al.*, 1930; Thompson and Van Cleve, 1936; Thompson *et al.*, 1936). Oceanographic observations made along sections from the coast, offshore to the central part of the Gulf of Alaska, permitted a calculation of geostrophic currents parallel to the coast (Fig. 18). The strongest flow occurred just off the continental shelf and was counterclockwise around the Gulf. The greatest irregularities, both in direction and speed, occurred in the waters overlying the continental shelf. "Coastal", "Intermediate" and "Ocean" waters were defined from values of chlorinity.

Some results of drift bottle experiments, shown in Figure 19, indicated the existence of a counterclockwise current around the Gulf, and that this current transported water into the Bering Sea through the Aleutian passes. Experiments off the North American coast indicated that the eastward flowing water divided well south of lat. 47°N. in March, and near

lat. 50°N. during the summer. This division was found to conform to the latitude of separation of residual winds with a northerly component and those with a southerly component, as calculated from the Pilot Charts of the U.S. Hydrographic Office.

Tully (1937) using data from a small area seaward of the coast of Vancouver Island (approximately 100 miles) showed the presence of a southeastward current which extended to within 10 miles of the coast.

The next major investigation was carried out by Goodman and Thompson (1940). They used T-S relationships to demonstrate the major features in this area and identified five water masses. The water immediately south of the Aleutian Islands, which flowed westward, was associated with the Alaska Current (Alaskan Stream). Southeast of the Stream in the central Gulf of Alaska was found " South Aleutian water " within which surface temperatures and salinities were fairly constant. To the eastward of this, the water which flowed northward past the coast of British Columbia and southeast Alaska was identified as the " Washington drift ". Further inshore, the water along the continental shelf was called " Coastal water ". Finally, the eastward flow, southward of these water masses, was called the " North Pacific Stream " (West Wind Drift). The existence of clockwise eddies at the boundaries of these water masses was noted.

Although considerable data were gathered during 1949 (Scripps Institution of Oceanography, 1957) and in the following years, there were no further major contributions in this area until Doe (1955) published the results obtained from cruises covering the " Offshore " waters of the British Columbia coast during 1950–51. These cruises provided the first good synoptic data in the eastern Subarctic. Doe recognized the existence of three distinct zones in the water structure. They were identified in the T-S relationships and in plots of the properties versus logarithm of the depth as the surface zone (0–94 m.), halocline (93–153 m.) and the lower zone. He concluded that the role of the halocline was to act as a barrier to the passage of water from the lower zone to the surface zone or vice versa; thus, the temperature at the bottom of the surface zone (top of the halocline) could be considered a quasi-conservative property of the surface water mass. Further, the temperature at the top of the lower zone (bottom of the halocline) could be considered a conservative property of the lower zone. The salinity at the bottom of the halocline was approximately 33.8‰.

Doe also concluded that the currents were weak and variable in this area. At individual stations, the direction of currents at different levels was similar to that at the sea surface, but the velocity decreased with depth until at 300 metres it was approximately one-half that at the surface. Further, the general direction of flow suggested by isentropic charts was similar to that indicated by the calculated dynamic topography (geostrophic currents). The water identified by Goodman and Thompson (1940) as " South Aleutian water ", was found immediately westward of the offshore region and was called " mid-gulf water " (Fig. 20). Differences between the conditions observed in the two summers (1950 colder than 1951) were noted, and believed to be related to the position of division of the water flowing from the west. This work laid a sound foundation on which future studies in this area were based.

Prior to 1955 other studies were carried out in the area by the Department of Oceanography, University of Washington. Barnes and Paquette (1954) discussed currents off the coast of Washington. Their conclusions were in general agreement with the previous works, and indicated a region of division well offshore at about lat. 45°N.

Scripps Institution of Oceanography collected data off the west coast of the United States in winter and summer in conjunction with their Marine Life Program conducted for the California Cooperative Oceanic Fisheries Investigations. Most of this work is not of major interest for this review because it was limited to the coastal areas and southern extremity of the eastern Subarctic Region.

B. Investigations Since 1955

Although the oceanographic surveys have been continued to the present time, this review considers only the extensive data collected during 1955 through 1959 by agencies of Canada, Japan and the United States of America. Studies of these data have resulted in significant advances in an understanding of the Subarctic Pacific Region, in particular, an insight into water structure and mechanisms and a more complete understanding of the circulation, both of which have permitted identification of water masses and domains.

The sources of data are given at the end of the report. Most of the individual cruises directly connected with the INPFC and some preliminary results have been described in the annual reports of the International North Pacific Fisheries Commission (1957, 1958, 1959, 1960).

1. *1955.* Although some exploratory fishing operations for the INPFC were made in 1953 and 1954, it was not until 1955 that any appreciable oceano-

graphic work covering the Subarctic was accomplished. The NORPAC expeditions provided the first synoptic oceanographic coverage in the North Pacific Ocean north of lat. 20°N. (Fig. 21). The data are presented in atlas (Oceanic Observations of the Pacific: 1955, 1960a) and tabular form (Oceanic Observations of the Pacific: 1955, 1960 b). Also, observations were made by the Department of Oceanography, University of Washington, from the vessels *Mitkof*, *Paragon* and *John N. Cobb* engaged primarily in exploratory fishing (Favorite and Love, 1957).

2. *1956.* Although the year 1956 fell between the extensive NORPAC expeditions and the subsequent acceleration of oceanographic work during 1957 through 1958 as a result of the International Geophysical Year, good oceanographic coverage was obtained almost exclusively by agencies contributing to the INPFC program (Fig. 22). The figure is somewhat misleading as to the amount of adequate data available for this period. It should be pointed out that except for the data obtained from the *Oshoro Maru*, *Tenyo Maru*, M. V. *Brown Bear* and H.M.C.S. *New Glasgow*, observations deal with bathythermograph observations, with near surface waters, or the depth intervals of sampling were so large that interpolation between depths was difficult or inaccurate.

During 1956 the Canadian group expanded their oceanographic program aboard C.C.G.S. *St. Catharines* occupying Ocean Weather Station " P " (lat. 50°N., long. 145°W.) during alternate six week periods, to include complete oceanographic observations. Bathythermograph observations were maintained on the other vessel, C.C.G.S. *Stonetown*, occupying this station. These and subsequent data from this position made it possible to understand some of the mechanisms associated with the temperature and salinity structures.

3. *1957.* In January, the Canadian program was expanded to include a winter oceanographic cruise in the eastern Subarctic (Fig. 23). This cruise provided information on the winter structure and circulation and eventually permitted a better interpretation of summer conditions.

In summer, an oceanographic group was established within the Bureau of Commercial Fisheries Biological Laboratory, Seattle, which took over the United States oceanographic research in the INPFC previously conducted by the Department of Oceanography, University of Washington. The work was carried out on exploratory fishing vessels, principally in the Bering Sea and in the waters immediately south of the Aleutian Islands. An expansion of oceanographic work aboard these vessels made it possible to give a good assessment of the oceanographic conditions in this area. Data from these cruises when combined with those from Japanese and Canadian surveys maintained continuity of observations across the Subarctic. The resultant coverage which includes various cruises conducted under the International Geophysical Year (IGY) Program is shown in Figure 24.

4. *1958.* A winter oceanographic survey was carried out in the eastern Subarctic by the Canadian group to monitor the oceanographic conditions in the area and to learn if the circulation was accelerated during the winter months near the edge of the continental shelf. Also, data from depths greater than 2500 metres were obtained, which are requisite to deep current studies. Data were also gathered by the Department of Oceanography, University of Washington (Fig. 25).

In 1958, realizing the necessity of extensive synoptic oceanographic coverage in the central area south of the Aleutian Islands, which the United States exploratory fishing vessels were unable to obtain independently, the Canadian group assisted in obtaining data in the central Aleutian area and the Bering Sea; and the Bureau of Commercial Fisheries Biological Laboratory, Honolulu, extended their oceanographic observations, taken in conjunction with their albacore studies, as far north as practicable. These cruises, as well as the excellent coverage provided by various Japanese agencies in the western Pacific and the work off the coast of the United States by the Department of Oceanography, University of Washington, provided the best oceanographic coverage ever obtained in the Subarctic Region (Fig. 26). Dodimead and Favorite (1961) have published an Atlas of these combined data. An Atlas of the Japanese Oceanographic Project for IGY, 1957 and 1958, has also been published (National Committee of IGY, 1960).

5. *1959.* Conditions in the eastern Subarctic were again monitored during the winter period (Fig. 27). These data have been published in atlas form (Dodimead, 1959).

During summer 1959, the absence of supporting operations to the southward limited the coverage in the central Subarctic (Fig. 28). However, extensive cruises by United States and Japanese vessels provided the best coverage to date in the Bering Sea. At the same time the Canadian cruises in the eastern Subarctic were extended southward. Also, measurements were made to depths of 4000 metres at some stations.

6. *Subsequent work.* Although the results of the oceanographic programs presented in this report are based upon data collected during the cruises 1955

through 1959, spring and summer surveys are still being made. The data have been or are being published. Winter data in the eastern Subarctic were taken in 1960 and published in atlas form (Dodimead, 1960) and winter data from the central Subarctic were taken for the first time in 1962 (Favorite *et al.*, 1962).

IV. STRUCTURE AND MECHANISMS

A. Salinity

The salinity structure is a unique and permanent feature of the Subarctic Pacific Region. Most of the characteristics of the salinity structure and its variations have been described from time-series data at Ocean Station " P " (lat. 50°N., long. 145°W.) by Tabata (1961) and Dodimead (1961 a). Mechanisms for this structure and its significance have been proposed by Fleming (1958), Tully and Barber (1960), and Dodimead (1961 a).

The principal features of the salinity structure are apparent in Figure 29 which shows a sequence of three typical structures from summer through winter to the next summer at Ocean Station " P ". The permanent features are (1) an *upper zone* from 0 to about 100 metres depth; (2) a *halocline* in which the salinity increases by about 1‰ in the depth interval from about 100 to 200 metres; and (3) a *lower zone* in which the salinity increases gradually but uniformly to about 34.4‰ at 1000 metres depth. Below this depth the salinity increases very gradually to 34.67‰ at 4000 metres.

The bottom of the halocline (or top of the lower zone) can be defined with considerable accuracy (± 0.1‰) by the isohaline surface of salinity = 33.8‰. Tully and Barber (1960) suggested that the bottom of the halocline is the ultimate limit of downward transfer of water from the surface and at this level the transfer of water is unidirectional upward. They concluded that the lower zone water is entrained into the upper zone through the halocline but fresh water is conserved within the upper zone and halocline; that is, the features of a simple estuarine system are present.

The most significant variations in the salinity structure occur within the upper zone and are primarily due to seasonal effects. Dodimead (1961a) has described these variations from a sequence of salinity structures at Ocean Station " P " shown in Figure 30. Temperature structures are included in the figure because in this zone both structures are influenced either directly or indirectly by the same seasonal processes. For the following discussion it should be noted that the geostrophic flow in the vicinity of Ocean Station " P " is generally zonal, but, more important, slow (2 miles/day). Hence, within the time period considered here, the waters in the area are subjected to climatic conditions similar to those at Ocean Station " P "; thus, they can be regarded as having resided there.

Tabata (1961) has defined the periods of heating, April to September, and cooling, October to March, at Ocean Station " P " (Fig. 31). During the late cooling period, the salinity and temperature structures are isohaline and isothermal from the surface to the top of the halocline, and during the heating period, April to September, a secondary halocline is formed in the upper zone coincident with the thermocline (Fig. 30). Below the secondary halocline the salinity structure instead of being isohaline, as during the cooling period, develops a slight gradient to the top of the main or principal halocline. This latter change in structure can be related to the " entrainment " processes associated with the estuarine mechanism (Tully and Barber, 1960) or possibly vertical eddy diffusion. Either of these processes tend to increase the salinity and create a gradient in this part of the upper zone.

During the early cooling period, October through November, the secondary halocline decays, sinks and eventually vanishes into the permanent halocline. As a result, a relatively shallow isohaline and isothermal layer and a larger halocline (ΔS) is formed. This process continues throughout the cooling period until the waters become homogeneous to an ultimate depth defined in the salinity structure by the top of the halocline. This sequence of events is shown in Figure 32.

The upper zone is established during the period of cooling, and although it undergoes changes, it can be identified throughout the period of heating. It is again re-established during the winter period. This sequence recurs from year to year. Tabata (1961) has discussed the seasonal values of salinity at selected depths of the water at Ocean Station " P " for the two years August 1956 through July 1958. The variations are most marked in the upper zone (0–100 m.) (Figure 33) and are consequences of the growth and decay of the seasonal thermocline which is diseussed under Temperature (p. 12). The seasonal thermocline effeetively protects the underlying waters from surface effects such as warming and dilution. The excess precipitation during summer accumulates above the thermocline resulting in minimum surface salinities at the end of the heating season. During this time, the salinity of the water below the thermocline is increased by upward transfer (entrainment) of more saline water from the halocline, and the highest salinity values in

the sub-thermocline zone (at and near the bottom of the upper zone, e.g., 100 metres) are found in autumn. Thereafter winter turnover mixes the surface waters to homogeneity down to the depth of the top of the halocline, resulting in a reversal of conditions; the salinities at the surface attain their highest values and salinities at the top of the halocline (approximately 100 metres) attain their lowest values.

In 1953 Tully (1956) showed that the salinity zone structure of a simple estuarine system could be accurately delineated by plotting salinity as a function of the logarithm of the depth. In such a plot the upper and lower limits of the halocline (or transition zone) are characterized by two well defined discontinuities. Since then this method has been used by Doe (1955) and Dodimead (1961 a) to define the features of the salinity structure in the Subarctic. Typical salinity profiles (salinity *vs.* logarithm of the depth) of the zone structure in the northern Pacific are shown in Figure 34. It is evident that the simple zone structure, similar to that at Ocean Station " P ", predominates over nearly all the oceanic part of the Subarctic. This is confirmed in the vertical sections of salinity. The structure is dependent upon surface dilution and the absence of extensive vertical mixing, otherwise modification of the simple 3-zone structure occurs; the halocline expands and its lower limit becomes less distinct. Extreme modified structures occur in the Okhotsk Sea and the island passages (Kuril and Aleutian) (e.g., see Station A, Figure 34).

Figure 35 shows a sequence of salinity structures in the area extending from lat. 50°N. to the Subarctic boundary. The simple 3-zone structure is present, but the halocline and hence upper zone becomes progressively less pronounced southward. Near the boundary an increase in the salinity at the bottom of the halocline occurs (33.8‰ to 34.0‰). In this area, the features of the upper zone become complex and salinity inversions may occur. However, the water column is stable because of the marked temperature gradients.

At the Subarctic boundary the upper zone and halocline vanish.

B. Temperature

Within the Subarctic Region, the temperature structures have marked variations, both seasonally and with locale. The principal features of the temperature structures can be described from data observed at Ocean Station " P " and presented in Figure 36 (zones identified in the salinity structures (Fig. 29) are shown). In summer, there is an isothermal or near isothermal layer, corresponding to the isohaline layer, extending to about 30 metres depth. Below this layer, a marked thermocline is present which corresponds in position to the secondary halocline extending to about 75 metres depth. Below this depth, one of two conditions occurs; either the temperature of the water decreases continually with depth, or increases slightly within the halocline. In both cases there is a negative gradient in the lower zone.

In the winter, the isothermal (and isohaline) layer extends downward to the top of the halocline (approximately 100 metres depth). Below this level and in the halocline there may be a positive or a negative gradient depending on the severity of the cooling during the winter period. The occurrence of these structures and the magnitudes of the gradients are directly related to the amount of surface cooling and the temperature of the waters in the halocline. In the lower zone, the temperature decreases with depth, similar to the summer structures.

Figures 31 and 37 define the annual cycles of heating and cooling and of temperature structures at Ocean Station " P ". In April, with the advent of the heating period, a thermocline is formed. The overlying waters continue to warm and the thermocline grows until the end of the heating period. The heat is not transferred below the thermocline and a remnant of the cold isothermal (isohaline) structure formed during the previous winter remains. During the cooling period, the surface layer cools and deepens; the thermocline decays, becomes abrupt and sinks. Usually by March it vanishes along with the secondary halocline.

Tully and Giovando (1962) have illustrated and described the mechanics of this growth and decay of the thermocline in the semi-daily bathythermograph observations at Ocean Station " P ". They concluded that in the oceanic areas away from coastal turbulence three dominant processes are involved; heating, cooling, and wind mixing. The mechanics of these processes are considered similar in all oceanic areas, differing only in degree from place to place and time to time.

Heating is due mainly to radiant energy from the sun which occurs only during daytime. Cooling is due to evaporation, back radiation and conduction of heat from the sea surface, and is continuous day and night. Hence, there is a diurnal cycle of surface heating and cooling. During the heating period, April to September (Fig. 31), some of the heat gained in daytime is retained through the night; hence, there is a cumulative heat gain. Usually, there is some wind so that a shallow (1–3 metres) mixed layer is formed.

Below this, there is a small negative thermocline separating the warmed surface waters from the unwarmed deeper waters. The heat will be lost, and the associated thermocline will vanish, if the nighttime cooling exceeds the daytime heating. If the heat is not lost it is mixed downward and the associated thermocline is found at a depth proportional to the strength of the winds. In these cases the thermoclines are transient. Normally they cannot persist for more than a few days and eventually join the seasonal thermocline. This seasonal thermocline can only be destroyed by violent turbulence or by a long continued process such as winter cooling.

The positions of the seasonal and transient thermoclines for the period March through November, 1956, at Ocean Station " P " are illustrated in Figures 38a, b, c. Temperature-depth profiles for specific periods are also shown. These figures show most of the types of structures that can occur. Transient thermoclines first occurred in April, and a seasonal thermocline was formed at the end of the month (Fig. 38a). Thereafter, the transient thermoclines occurred with increasing frequency throughout the heating period. Each transient provided a small increase in the temperature in the surface layer, and added to the magnitude (ΔT) of the seasonal thermocline. Through May, the seasonal thermocline deepened in the presence of increasing winds. At the beginning of July (Fig. 38b), a period of light winds, a second thermocline was formed, overlying the old one. Usually the winds are sufficient to mix the thermocline down so that a single seasonal thermocline is formed, as occurred in 1955, 1957, 1958 and 1959. However, in 1956 all heat additions (transients) contributed to the upper thermocline while the lower thermocline remained unchanged. During a period of very light winds, August 9 to 17, a third, shallower thermocline formed (Fig. 38b). However, as soon as the wind increased this was driven down to the next level and joined the underlying thermocline. By about mid-September, transients no longer occurred (Fig. 38c). By October, the upper thermocline had been mixed downward and joined the lower thermocline. Thereafter the thermocline was eroded and deepened.

The depths of the upper and lower limits of the thermocline oscillated between three and five metres from their mean depth and at times as much as 20 metres from their mean depth. This is attributed to internal waves having a spectrum of periods from several minutes to at least half a day (Tully and Giovando, 1962). Further, the oscillations of the top and bottom of the thermocline are not always synchronous, hence the thickness of the thermocline may vary considerably.

Because of this ambient variation it is not possible to determine the gradient, $\Delta T/\Delta Z$. However, these variations do not affect the determination of the temperature difference in the thermocline which accompanied by the mean depth and standard deviation of its depth limits provides the only accurate description of the temperature structure.

Unless affected by processes of convergence or divergence, three general rules of behaviour may be deduced. First, the thermocline does not ascend toward the surface. This would require the unmixing of the warmed and unwarmed waters which cannot be accomplished by any mechanical means. However, the mixed layer can deepen in the presence of any process which will increase the mixing, or remove the heat. Second, heat is not transferred downward through the thermocline. Such transfer requires mixing, which must lower or destroy the thermocline. Hence, each thermocline forms a cover protecting the waters below it against further heating from the surface. The upper limit of a thermocline defines the depth of existing local surface influence. Third, in and below the thermocline the temperature and structure can only be changed by internal processes, such as mixing or advection. In most oceanic areas such processes are slow, hence aside from internal waves the sub-thermocline temperature structure is constant, or changes slowly during periods of weeks or months.

These discussions are summarized from Figure 39 which shows, in generalized form, the sequence of structures throughout the year in the upper 200 metres of depth. The oceanographic structures in the surface layer respond to the local surface processes (heating, cooling, wind mixing). The seasonal thermocline reprcsents the cumulative effects of these processes and marks the limit of their influence. The depth of a seasonal thermocline remains fairly constant from the end of June until the beginning of the cooling season in mid-September. At this time cooling and evaporation become dominant. The density of the surface waters increases and convective mixing occurs. The process erodes the thermocline gradually through the cooling season, below the limit of any wind mixing. In the Subarctic Region the process stops at the depth of the permanent halocline because its stability precludes further downward mixing. The effects of surface cooling usually reach this depth in January or February. Thereafter the whole upper zone may continue to cool.

The waters immediately above the halocline are

exposed to surface influence (cooling) only during the short interval in late winter when the seasonal thermocline has vanished. The properties of these waters are established at this time and are preserved within reasonable limits through the remainder of the year, under the seasonal thermocline. Figure 40 shows the temperature at the surface and 100 metres depth observed twice daily at Ocean Station " P ". These data, which reflect ambient variations due to internal waves, show, in most years, periods of cooling or warming at 100 metres depth during which temperature changes do not exceed 1°C. In most of the Subarctic these waters are easily recognized in the salinity structure, and occur at the top of the halocline (bottom of upper zone) (Dodimead, 1961a).

Other features of the temperature cycle of the waters at Ocean Station " P " and in the eastern Subarctic have been reported by Hollister (1956), Robinson (1957) and Tabata (1961). Sea surface temperatures reach a maximum (13–14°C.) in late August and a minimum (5–6°C.) in late March at Ocean Station " P " (Fig. 41). The annual range is between 7°C. and 8°C. This is the range noted in the sea surface temperature charts (Fig. 12a, c) and may be assumed to be related to the uniformity of incident energy in the Subarctic (Fig. 10, Tully and Dodimead, 1957). Too, the annual cycles of air and sea surface temperatures are similar at Ocean Station " P " (Fig. 42). In winter, the rate of change of air temperature is not as uniform as that of the sea surface temperature. The most marked temperature variations in the water column occur from surface to a depth of 30 metres (Fig. 43). At 50 metres depth, the annual variations are one half the magnitude of those at the surface.

Typical summer temperature structures in the Subarctic are shown in Figure 34. In the western Subarctic, particularly in the Okhotsk and Bering Seas, the temperature structures exhibit a marked positive gradient within the halocline. This results in a subsurface minimum, commonly referred to as dichothermal water (Uda, 1935) which is always associated with the bottom of the upper zone; and a subsurface maximum, commonly referred to as mesothermal water, which occurs in the halocline. The coldest dichothermal water occurs in the regions of winter ice cover.

Uda (1962) has classified the dichothermal structure according to the mode of formation and subsequent behaviour. One type is the consequence of the seasonal cycle of heating and cooling. It occurs in areas where, during the winter, the waters in the upper zone become colder than the waters in the halocline (western Subarctic, particularly Okhotsk and Bering Seas and the northern Gulf of Alaska). A positive thermocline is formed in the halocline below the isothermal upper zone. With the advent of the summer heating, a negative thermocline is formed and continues to grow through the heating period. In this type of dichothermal structure there is an isothermal " temperature-minimum " layer situated between an upper negative and a lower positive thermocline. The characteristic temperature (T_{min}) apparently changes very little during the course of the summer period. This is consistent with the thermocline model deduced at Ocean Station " P ".

A second type of dichothermal structure originates by the same process in the areas of sea ice formation, primarily in the Okhotsk Sea. The cold, more saline iso-layer remaining after the formation of ice extends to depths between 75 and 150 metres. The temperature of this layer is between –1.8°C. and 1.0°C. The layer (in the Okhotsk Sea) follows the persistent circulation (p. 18) and moves through the middle Kuril passages into the western Pacific. Because of mixing along its path, especially in the island passages, the layer becomes warmer (to about 1°C.). A portion of the layer underruns the upper layers of the warm (to 20°C.) saline (to 35‰) Kuroshio to form the greatest part of the Oyashio Undercurrent. The passage at depth of the water through the Kuril passages and its (modified) continuation as the Undercurrent can be " traced " by the horizontal distribution of dichothermal temperature or by means of a salinity minimum at depth. The outflow through the middle Kuril passes persists throughout the entire year. The strength of the Undercurrent varies from year to year and appears to be related to the meteorological conditions in the area (Kajiura, 1949).

In the lower zone the temperature generally decreases with depth to about 3°C. at 1000 metres depth and about 1.5°C. at 4000 metres depth. However, in the Okhotsk Sea, the temperatures below the subsurface minimum (dichothermal temperature) usually increase with depth to about 3°C. at the limit of the observations.

The temperature profiles along a north-south section (Fig. 35) show that the greatest regional changes occur in the lower zone. Near the Subarctic boundary, a marked negative gradient occurs from the limit of the upper zone to about 600 metres depth. However, at about lat. 49°N., a slight temperature maximum is present at depths of about 400 metres. This feature has been observed as far east as long. 155°W. but a little further to the south (approximately lat. 47°N.). This maximum is not a direct result of the seasonal heating and cooling process since it

occurs well within the lower zone. Presumably it is associated with advection.

C. Dissolved Oxygen

The principal features of the dissolved oxygen structure can be described from data observed at Ocean Station " P " (Fig. 44). The summer structure exhibits a fairly marked maximum at about 30 to 50 metres depth. From about 100 to 300 metres depth, an oxycline is present. The values then decrease gradually to a minimum at about 800 metres depth, and then increase below this. In winter, a relatively homogeneous upper layer corresponding to the isopycnal upper zone exists. Other than the changes in the upper zone, the structure is relatively constant throughout the year.

In Figure 45 are shown the dissolved oxygen concentrations at selected depths. In the upper zone (0–100 m.), marked annual variations occur, especially in the upper 30 metres of depth. The near surface waters (0–30 m.) are saturated or supersaturated with dissolved oxygen throughout the year. However, the solubility and hence concentration also varies with temperature; this results in maximum values in late winter, and minimum values in late summer without considering biological factors.

There is little evidence of annual variations below a depth of 100 metres, the limit of the upper zone. However, in both the halocline and the lower zone, appreciable variations with a period greater than one year are evident.

Typical oxygen profiles corresponding to the salinity and temperature profiles already discussed are shown in Figure 34. These profiles show the existence of a fairly sharp oxycline between 100 and 300 metres depth throughout the northern Subarctic. But, as shown in Figure 35, near the Subarctic boundary the oxycline becomes indistinct and extends from near the surface to about 600 metres depth.

D. Vertical Sections of Salinity, Temperature and Dissolved Oxygen

Several vertical sections of salinity, temperature and dissolved oxygen and their locations for each year, 1955 through 1959, are shown in Figures 46 to 99. Where possible, the locations of the sections are the same for each year. Oxygen data were not always available. The figures, which show the distribution of properties from the surface to 1000 metres depth, identify the features of structure in the Subarctic and permit comparison of conditions during these years.

1. *Salinity.* In the figures showing salinity structure, an upper zone, halocline and lower zone have been defined, where adequate data were available from logarithmic plots. In those figures where the upper zone has been identified, the absence of a halocline zone indicates that no sharp discontinuity existed between the halocline and the lower zone.

In general the upper zone extended to depths generally less than 150 metres. A slight vertical salinity gradient, or a secondary halocline, associated with the thermocline existed in this zone during the summer. The bottom of the halocline usually corresponded in position to the depth of the isohaline of 33.8‰.

Near the Subarctic boundary the salinity at the bottom of the halocline increased to about 34.0‰ and a salinity minimum (approximately 33.9‰) occurred in the lower zone, close under the halocline. This salinity minimum deepened to the southward.

Off the coast of Japan, the sections (Fig. 47, 68, 80 and 91) show a marked salinity boundary at lat. 40°N. which extended from the surface to a depth of about 400 metres and clearly indicates the marked discontinuity of oceanographic structure and properties at the confluence of the saline Kuroshio and less saline Oyashio systems. Eastward of the area, this feature can be identified but was not so pronounced.

In a section parallel to the Kuril Islands (Fig. 48) a marked deepening of the isohalines occurred off the southern end of the Islands, and water of salinity of 33.6‰ was present at a depth of 500 metres. Such water generally occurred above 200 metres depth and within the principal halocline. This feature is presumably a result of an outflow from the Okhotsk Sea where this type of structure is found. A similar section for the following summer, 1956, does not show this feature to be so pronounced (Fig. 55). As suggested by Kajiura (1949), the intensity of this outflow from the Okhotsk Sea appears to be variable.

A striking feature of the north-south sections through the Aleutian Islands and the Gulf of Alaska is the dome-like configuration of the isohalines in the lower zone. It is easily recognized in all sections in this area. Examples of this feature are shown in Figures 83 to 85. This anticline is a permanent feature and appears to be continuous from the middle of the Gulf of Alaska westward along the southern side of the Aleutian Islands to at least long. 175°E. The halocline was continuous throughout the area of the dome in all available data. However, the upper

zone and halocline were compressed into a shallower depth interval and salinities were usually greater than those in adjacent areas. Too, the lower zone water of salinity greater than 34.0‰ was continuous into the Subtropic Region. Such features suggest a source of saline water into the Subarctic. Immediately northward of the dome, the isohalines dipped downward markedly, indicating a relatively strong westward current (Alaskan Stream) which carries relatively warm, dilute surface water along the southern side of the Aleutian Islands. In the shallow Aleutian passages, turbulent mixing destroys the zone structure.

In the Bering Sea, the upper zone and halocline extended to greater depths than south of the Aleutian Islands. Also, in some areas of the Bering Sea, the principal halocline and lower zone are not easily distinguished and the salinity gradient extended from the bottom of the upper zone to approximately 600 metres depth. These conditions are shown in Figure 95. Over the continental shelf relatively dilute water extended from the surface to the bottom, and a marked horizontal gradient occurred at the edge of the shelf (see Fig. 58). These are common features in all high latitude continental shelf areas. However, unlike conditions off the British Columbia coast, the fresh water was not dissipated seaward off the continental shelf to any extent.

In the eastern Subarctic, the summer latitudinal sections for these years showed that the upper zone and halocline depths did not vary markedly and could always be defined (see Fig. 98). There were no marked horizontal gradients at the surface in the oceanic areas. The winter data (Fig. 89) reflect the same features except that the upper zone was homogeneous.

Off the North American coast at lat. 40°N. relatively dilute water usually extended as far west as long. 140°W. (see Fig. 53). Near the coast, at this latitude, relatively cold saline conditions existed as a result of upwelling, produced by the predominantly along-shore winds during the summer periods (McEwen, 1912).

2. *Temperature.* Vertical sections of temperature are also shown in Figures 46 to 99. All summer sections show that a marked thermocline occurred in the upper zone between 30 and 75 metres depth. Above the thermocline, the water was generally isothermal (and isohaline). Sub-thermocline temperature minima (dichothermal water) which occurred at the bottom of the upper zone (compare with salinity sections) were found over a large part of the Subarctic. Such minima were lowest in the Okhotsk and northern Bering Seas. Below the minima, there were corresponding temperature maxima (mesothermal water) in the halocline.

In winter, the thermocline was absent and the waters were isothermal (and isohaline) to the top of the halocline.

Off the coast of Japan at lat. 40°N. a marked temperature boundary, corresponding to the salinity boundary, was present (Fig. 47, 68, 80 and 91). However, in the mid-ocean area it becomes less distinct, necessitating the use of salinity structure to define the Subarctic boundary (p. 3).

Figure 48 indicates the same physical feature as seen in the salinity section along the Kuril Islands; namely, a deepening of the isotherms at the southern end which confirms the outflow of cold water from the Okhotsk Sea.

In the Gulf of Alaska and south of the Aleutian Islands, a dome-like structure similar to that in the salinity section occurred in the lower zone (e.g., Fig. 83 to 85). Northward of the dome, the waters were warm (and dilute) and are associated with the westward flowing Alaskan Stream. In the central part of the Region, south of the Aleutian Islands, the configuration of the isotherms was markedly different from that of the isohalines. Southward of lat. 45°N. and below the summer thermocline there was a fairly marked vertical gradient which became greater and extended to deeper depths toward the Subtropic Region.

Between lat. 46°N. and 42°N. near long. 145°W. in summer 1959, there was a distinct temperature minimum at the bottom of the upper zone and a maximum immediately below it in the halocline (Fig. 97). This feature was absent in the temperature structure to the eastward and in both of the latitudinal sections along approximately lat. 48°N. and 38°N. (Fig. 98 and 99). This dichothermal water was apparently isolated offshore and was not present in this area during the previous years.

In the Bering Sea (Fig. 58), extremely cold water (−1.0°C.) below the summer thermocline was present in areas over the continental shelf, but, because of the low salinity of these waters, they were not of sufficient density to cascade over the continental shelf and create an intermediate water in the Bering Sea.

3. *Dissolved oxygen.* The oxygen sections are included with the salinity and temperature sections for each year (Fig. 46 to 99).

In the upper zone, as defined in the salinity structure, a marked oxygen maximum generally occurred between 30 and 50 metres depth in summer and was approximately coincident with the summer thermocline. Concentrations within the maximum were usually greater than 0.6 mg. at./l.

In the Gulf of Alaska and south of the Aleutian Islands, the isopleths of oxygen showed an anticline similar to that noted in the salinity and temperature sections (e.g., Fig. 83 to 85). Also in this area, the oxycline was closely associated with the halocline but southward of the dome, the oxycline deepened and was no longer coincident. Rather, the gradient and configuration of the isopleths of oxygen were similar to those of the isotherms. Relatively high concentrations were found at considerable depth near the Subarctic boundary and because of high surface temperatures at this latitude relatively low surface values were found.

The oxygen minimum which usually occurred between 800 and 1000 metres depth near the Subarctic boundary rose in the area of the dome to between 400 and 600 metres depth (e.g., Fig. 73).

In the Bering Sea, the isopleths of oxygen had nearly the same configuration as the isohalines. Also, values in the upper zone were greater (0.6–0.8 mg. at./l.) than elsewhere in the Subarctic.

In the eastern Subarctic during winter, oxygen concentrations were relatively uniform in the upper zone (Fig. 64). Maxima were observed in winter, 1957, and were usually found at slightly greater depths than during the summer periods (Dodimead, 1958). Also, slightly greater concentrations were found in the surface waters in winter compared to summer. This is presumably due to increased solubility in the cold water and marked aeration due to storms (compare Fig. 64 and 73).

V. CIRCULATION

Oceanic circulation can be deduced by various methods such as direct-current measurements; distribution of properties on selected surfaces (i.e., at standard depths or on a constant property surface); geostrophic currents or transports compared to an arbitrary reference level; release and recovery points of drift bottles, floats or cards; or theoretical considerations of the effect of wind stress on the sea surface. All these methods except accurate and complete direct-current observations have some short-comings. But, until enough ships and time are available to carry out direct-current measurements, indirect methods must be used. These methods when mutually supporting, permit a reasonably accurate and reliable interpretation of the circulation.

A. Geostrophic Currents

In the absence of direct-current measurements, the most common method of deducing the circulation is from geostrophic currents (calculated from values of temperature and salinity at known depths). They are usually presented as contoured fields of anomalies of dynamic heights (geopotential topography). In such charts, the flow is presumed to be along the contours and the speed is proportional to the gradient across them.

There are a number of limitations to this method, one of which is the choice of a suitable reference level, since the method gives calculated currents which are relative to those existing at the reference level. Thus, if there is appreciable movement at the reference level, the calculated velocities will be different from those found by direct-current observations. A reference level at 1000 metres depth was chosen principally because there are not enough stations with data at greater depths.

Reid (1961) has shown the geostrophic flow at the sea surface with respect to the 1000 decibar surface to agree in general with the average of currents estimated from the set and drift of vessels, and those presented in various atlases for the Pacific Ocean. Further, Barnes and Thompson (1938) have suggested that in the Bering Sea there is little movement at the 1000 decibar level. Dodimead (1961 b) has also suggested that this is an adequate level, particularly to show the direction of flow in the eastern Subarctic. This conclusion was deduced from a comparison of the geopotential topographies of the sea surface relative to 1000 and to 2000 decibars (Fig. 100). The configuration of the isopleths, and hence the direction of surface flow, was almost identical. In some areas, some reservation must be placed on the velocities calculated from the 1000 decibar reference surface since it is apparent in Figure 100, which also shows the topography at 1000 decibars using 2000 decibars as a reference level, that there is some movement at the 1000 decibar level. South of lat. 50°N. the topography at depth was relatively flat, implying little relative movement, and hence in this area the surface velocities calculated from the 1000 decibar level must be fairly accurate. The greatest movement occurred in the northern part of the Gulf of Alaska particularly around the northern boundary of the Alaskan Gyre. Bennett (1959) has shown that during summer, 1955, in this area surface velocities relative to 2000 decibars were about 1.5 times those relative to 1000 decibars. Also, comparison

between drogue measurements made aboard the U.S.C.G.S. *Explorer* in 1959 and dynamic topographies computed from hydrographic data near the Aleutian Islands shows that the latter method does not result in true velocities in this area. This discrepancy, no doubt, applies to most areas contiguous to land or oceanic fronts.

Also, it is difficult to believe that a uniform reference level exists in a north-south direction in the Subarctic. Neumann (1955) has shown that the reference level rises from the Equator towards the Poles in the Atlantic Ocean. These problems should be investigated further but in spite of these limitations considerable information can be gained from geostrophic calculations. The circulation at the sea surface relative to 200 and 1000 decibars, and at 200 and 500 decibars relative to 1000 decibars are discussed. The choice of these particular levels is based on the features of the salinity structure. The 200 decibars surface coincides approximately with the bottom of the halocline (see Salinity, p. 11). This surface separates surface waters that are directly influenced by seasonal processes of heating, cooling, precipitation, evaporation and wind action, from the deeper waters whose properties are relatively constant. The circulation at 500 decibars represents the features of the circulation in the deeper waters.

1. *Surface relative to 1000 decibars.* The surface circulations relative to 1000 decibars are shown in Figures 101 to 108 and are schematically summarized in Figure 109. In the extreme western Pacific, the warm, saline Kuroshio Current moves northward along the Japanese islands and the main flow turns eastward at about lat. 36°N. (well south of the Subarctic boundary). This water continues eastward as the North Pacific Current to about long. 150°W. where it moves southward.

Part of the Kuroshio continues northeastward to about lat. 40°N. where it meets the cold southward-moving less saline current (Oyashio) which is present along the eastern side of the Kuril and northern Japanese islands. At the confluence of the two currents, extensive mixing occurs both horizontally and vertically. Water properties in this locality are extremely variable and complex and the area is characterized by eddies. This mixed water continues eastward as the " West Wind Drift ". Geostrophic calculations show that it has a much slower speed than the Kuroshio and advances at about 2–4 nautical miles per day (4–8 cm./sec.). Uda (1962) suggested this speed is relatively uniform to about 300 metres depth. The water continues to the eastward with a slight northward component which carries it to about lat. 45°N. in the vicinity of long. 180° where it continues eastward in a near zonal path to approximately 300 miles from the Washington-Oregon coasts. Here the water divides; part turns southward to form the California Current; a small part intrudes into the area off the coast of Vancouver Island, and then moves southward along the coast; and the remainder flows northward into the Gulf of Alaska. In the area of division, the currents are weak and variable.

The part of the Oyashio that does not actively mix with the Kuroshio and which has properties similar to those of the Bering and Okhotsk Seas moves northeastward, approaching within 60 miles of the Aleutian Islands in the vicinity of long. 180°. Most of this water moves eastward in a near zonal path at a rate of about two miles per day (4 cm./sec.) (Subarctic Current). It eventually flows into the Gulf of Alaska, and around the Alaskan Gyre, making its return, after some modification, in the strong (8–10 miles/day, 16–20 cm./sec.) westward flowing current (Alaskan Stream) along the southern side of the Aleutian Islands.

The remainder of the water forms a gyre with its centre at about lat. 50°N., long. 165°E. The water at the edge of the gyre mixes with the water of the Alaskan Stream, moves westward to the end of the Aleutian chain and into the Bering Sea west of Attu Island, where it moves eastward along the northern side of the Aleutian Islands mixing with the near surface water that has flowed northward through the Aleutian passages. Some of this mixed water flows northward over the continental shelf through Bering Strait into the Arctic Ocean. The main circulation is cyclonic (counterclockwise) and water in the northwestern Bering Sea flows southward along the Siberian coast. One part becomes the East Kamchatka Current, the other is absorbed in the cyclonic gyre present in the central Bering Sea. Some of the water of the East Kamchatka Current moves into the Okhotsk Sea through the northern Kuril Islands. Here the structure of the water is modified as it circulates in a slow cyclonic gyre, eventually moving out through the central passages of the Kuril Islands.

The surface circulation in the Subarctic is, for the most part, closed. It is a major gyre with several subsidiary gyres superimposed on it. As a result of studies concerning fresh water accumulation, Tully and Barber (1960) have suggested that six years are necessary for the round trip. Drift bottle experiments indicate that it may be as short as four years. Although some water is lost through Bering Strait, the main surface flow out of the Subarctic occurs at the Subarctic-Subtropic boundary through the California Current system.

The significant features of the Subarctic circulation are:

(1) A major gyre with four subsidiary gyres; Bering Sea, Western Subarctic, Okhotsk Sea and Alaskan. The Alaskan Gyre extends along the southern side of the Aleutian Islands.

(2) The confluence of the Oyashio and Kuroshio.

(3) The division of the waters off the North American coast.

(4) The strong westward flowing current (Alaskan Stream) immediately south of the Aleutian Islands.

It will become evident that most of these surface features of circulation persist at the deeper levels. In some cases they are clearly evident, but in others they are less distinct than at the surface.

2. *200 decibars relative to 1000 decibars.* This circulation is shown in Figures 110 to 117 and the persistent features are illustrated schematically in Figure 118. In general, the major features are similar to those at the surface relative to 1000 decibars. All four gyres are present. However, the eastern edge of the Western Subarctic Gyre appears to extend further eastward than at the surface. The zonal flow centered along lat. 45°N. divides nearer the North American coast than the surface flow in this area. Also, the water south of lat. 45°N. does not appear to intrude into the area off the coast of Vancouver Island.

In summer, a northward flow off the Washington-Oregon coasts occurred in all years except 1958. This is the California Undercurrent. In the western Subarctic there is a southward flow called the Oyashio Undercurrent. Throughout the Region, the speed of the flow at this level is about one half that at the surface.

3. *500 decibars relative to 1000 decibars.* The circulations at 500 decibars are shown in Figures 119 to 126. A schematic of this flow (Fig. 127) shows that it is similar to that at 200 decibars. However, the velocities are less, indicating a reduced flow in the deeper waters. The division of the flow off the North American coast appears to be further south than at shallower levels. Too, the main westward flow along the Aleutian Islands and associated with the Alaskan Stream does not appear to intrude as far into the central Bering Sea. Instead, the movement is generally westward almost to Kamchatka where it moves southward and circulates around the Western Subarctic Gyre or continues eastward.

4. *Surface relative to 200 decibars.* Earlier works usually considered that the surface circulation deduced from this level was the same as that deduced from a deep reference surface (e.g., 1000 metres) and this is true in some areas. However, as seen in Figures 128 to 135 and summarized in Figure 136, there are some obvious differences, particularly in the mid-ocean area and in the vicinity of the Aleutian Islands.

In the mid-ocean area, flow computed between the surface and 200 decibars has a component to the north; whereas, the flow at the surface and other levels referred to 1000 decibars moves in a near zonal path. In the western Subarctic, from the vicinity of the Kuril Islands, the surface water appeared to flow toward the Aleutian Islands as far eastward as long. 175°W. instead of 175°E. as shown in Figures 109 and 118. From 175°W. water appeared to flow into the Bering Sea through the Aleutian passages or westward along the southern side of the Islands and then into the Bering Sea.

The apparent flow at the surface relative to 200 decibars can only be regarded as a surface tendency and does not always indicate a flow or continuity. That is, the surface flow is dependent upon the flow in the deeper water and is included in the total flow shown in the 0 to 1000 decibar charts.

5. *Variations 1955 through 1959.* Any major changes in the circulation pattern would materially affect the distribution and structure of the waters. Some variations in the circulation have been noted and these generally occurred at all depths.

Dodimead (1961 b) has discussed the year-to-year variations in the geostrophic circulation in the eastern Subarctic. He showed that the most marked anomaly in the surface circulation occurred in 1958. There was a high in the dynamic topography about 200 miles off the British Columbia coast and, associated with this, a southward flow near the coast. In other years (1955, 1956, 1957 and 1959) there was a northward flow in the approaches to the coast. He suggested that changes that occurred in the surface flow were dependent upon the flow in the deeper waters.

At 200 decibars relative to 1000 decibars the area of division (at about lat. 45°N., long. 135°W.) was furthest south during 1958 (Fig. 115). Also, in 1957 and 1959, this circulation was slightly different to that observed in 1955 and 1956 but not to the extent observed in 1958. Dodimead (1961 b) concluded that these changes, in part, accounted for the observed changes in water properties off the British Columbia coast.

The surface flow into the Gulf of Alaska was more northward in 1958 than in other years. This feature was most apparent in the surface circulation relative

to 200 decibars (Fig. 133). Also, the centre associated with the Alaskan Gyre shifted westward. Presumably, more water flowed into the Gulf of Alaska during 1958, and hence into the Alaskan Stream. As a result, there was marked westward extension of the Alaskan Stream, which was apparently accompanied by a reduction in the extent of the Western Subarctic Gyre. Kitano (1958) has shown minor changes in the extent of the Alaskan Stream in other years.

Callaway (1960) has shown the oceanographic conditions and flow that occurred in the vicinity of the Aleutian Islands during summer 1957. Some seasonal and yearly variations that occurred in the temperature structure in this area are shown in Figure 137 (INPFC, 1959). Figure 137a shows the vertical temperature structures along three longitudes during July, 1957. The warm water associated with the Alaskan Stream (4°C.) was confined to the southward of the Islands at long. 165°W. and extended well below the depth of Unimak Pass (approx. 60 metres). At long. 175°W., the warm water extended north and south of the Islands indicating an intrusion of water into the Bering Sea near this longitude. Further westward at long. 175°E. this water was displaced southward of the Islands by the colder Bering Sea water. However, a year later (July, 1958) conditions at long. 175°E. were changed (Fig. 137 b). The Bering Sea water had retreated northward and warm water was found north and south of the Aleutian ridge. These structures show the variability of flow in the Alaskan Stream which is not immediately evident from the horizontal charts of geostrophic currents.

B. Drift Bottles

Drift bottles and floats have provided another method of ascertaining the general surface circulation. Sealed bottles, containing a questionnaire and promise of a reward, or floats with an identifying number, were released in significant numbers at known positions.

Some recent Japanese experiments have been successful in areas where the floats have been captured in gillnets by the high seas fishing fleets. The results of two programs (Taguchi, 1959; Hakodate Marine Observatory, 1961) in the western Subarctic and Bering Sea are summarized in Figure 138.

A limited drift bottle program has been carried out by the Biological Laboratory, Seattle, in the Aleutian area where the possibility of recovery is remote. However, some interesting recoveries have been made which indicate the flow from the central to eastern Subarctic (Fig. 139).

Numerous drift bottle releases (1000 bottles each) have been made by the Pacific Oceanographic Group in the eastern Subarctic, usually from Ocean Station "P". The returns were between 4% and 7%. Dodimead and Hollister (1958) analyzed these data and showed that there were gross fluctuations in the surface currents during the period 1956 through 1958 and these results agreed with the geostrophic circulation. Some of the results are shown in Figure 140 and a complete summary of the program is reported by Dodimead and Hollister (1962).

Because of the nature of such experiments only general conclusions can be drawn, but several features of the circulation are apparent. In most cases they are in agreement with those deduced from geopotential topographies. In some cases they show features of the surface circulation not readily apparent in the calculated currents. They show surface flow:

(1) northward between Attu and Komandorski Islands;

(2) from as far south as lat. 46°N. between long. 140°W. and 145°W. into the Gulf of Alaska;

(3) around the Gulf of Alaska (Alaskan Gyre);

(4) along the southern side of the Aleutian Islands, into the Bering Sea and eastward along the northern side of the Islands;

(5) circulating within the Subarctic Region;

(6) from the Subarctic Region into the California Current system, toward the Hawaiian Islands, and then westward to the Philippine and Japanese islands;

(7) around the Western Subarctic Gyre.

C. Wind-Induced Mass Transport

Some of the more advanced theoretical works on oceanic circulation (Freeman, 1954; Hidaka, 1955; Charney, 1955 a, b; Veronis and Morgan, 1955; Morgan, 1956; Veronis and Stommel, 1956; Veronis, 1956; and Arons and Stommel, 1956) have been reviewed by Bowden (1958). He states: "It is now generally accepted that the chief features of the mean circulation in the upper layers are due, directly or indirectly, to the wind stress. It is less certain to what extent the influence of the wind affects the deepest layers or how the circulation as a whole responds to change in the winds." Recently, Fofonoff (1962 a) has investigated these problems. This work has been based on the study of steady-state transport of mass in the oceans as a function of the curl of the wind stress by Sverdrup (1947), Stommel (1948) and Munk (1950). From these Fofonoff has developed a model for the computation of the steady-state transport.

Starting with the grid presentation of mean monthly barometric pressure he computes, in sequence, the gradient winds, the stress on the sea surface, the Ekman (surface) transport, the geostrophic transport and the total transport. The results of these computations have been published for each month since January 1955 (Fofonoff, 1960 a, b, c, d, e; 1961). These charts show the steady state that would result if the barometric pressure situation persisted, or if the ocean responded with a lag less than one month. Present indications are that the Ekman currents respond in a few days, hence much shorter (5-day) means should be used. However, the response at depth may be delayed or integrated in some manner over periods as long as eight months. The charts show the ultimate effect, and taken in sequence, month to month, indicate the trend of development of the flow.

The annual mean geostrophic transports for the years 1955–59 are shown in Figure 141. Fofonoff (1962 b) compared the mean geostrophic transport for the five-year period 1955–59 with the transport determined from the NORPAC data, 1955. Favorite and Morse (1962) compared the wind (mean geostrophic transport) and calculated geostrophic (volume) transport for July and August 1958 (Fig. 142). In general, these works showed good agreement between the two methods and therefore transports calculated in this manner can be considered an aid in the assessment of present, and possibly future, conditions.

VI. HORIZONTAL DISTRIBUTION OF SALINITY AND TEMPERATURE

Unique features of the salinity and to some extent the temperature structures provide a method of showing the continuity and distribution of water properties in the Subarctic. The horizontal distribution of salinity and temperature on the following surfaces are shown and discussed for the years 1955 through 1959: at 10 metres, at the bottom of the upper zone, on the surface of salinity = 33.8‰ (a convenient index for the bottom of the halocline), and on the surface of salinity = 34.0‰ (representation of the deeper waters).

The selection of surfaces of constant salinity for the horizontal presentation of properties is a departure from the usual procedure of using surfaces at standard depths or surfaces of constant density, but are preferable because of the unique salinity structure. Comparison of plots of temperature on constant density and on constant salinity surfaces show that they are similar because density is salinity dominated. Therefore, they are equally applicable for presentation of the conditions and features in the Subarctic. Because horizontal distributions show in greater detail the conditions discussed under vertical sections (p. 15) some duplication of discussion may occur.

A. Surface

Properties at the 10 metre level (Fig. 143 to 158) represent conditions in the mixed layer (surface to top of thermocline) in summer or in the upper zone in winter. They are considered to be more representative of the prevailing conditions than those at the sea surface, which are subject to diurnal variations.

1. *Salinity at 10 metres depth.* In general, the isohalines in the mid-ocean between lat. 35°N. and 45°N. tended to have a zonal configuration (Fig. 143 to 150). Along the coasts there were fairly marked gradients and irregularities in the distributions. These conditions are attributable to the current systems, land drainage and local winds. The least saline water occurred over the continental shelf from Bristol Bay to the Gulf of Anadyr and in the northern part of the Okhotsk Sea. These low values are primarily due to ice melt and local runoff.

Dilute water was also generally present off the Columbia River. Further south, off the coast of California, salinities were generally high, and are presumably a result of the lack of land drainage and the occurrence of upwelling associated with the northwesterly winds prevalent during summer periods. The same feature was observed off the coast of Vancouver Island in summer, 1959 (Fig. 150). Tully (1942) observed similar conditions in the approaches to Juan de Fuca Strait. Between the northern tip of Vancouver Island and the Queen Charlotte Islands (lat. 51°N. to 55°N.) low salinity water (less than 32.4‰) generally extended a considerable distance offshore, often in the form of tongues. Presumably, these are associated with the meandering characteristics of the weak and variable flow in this area (Doe, 1955).

A salinity maximum (32.8‰ to 33.1‰) was usually present in the Gulf of Alaska southward of Kodiak and the Shumagin Islands. This feature is considered to be associated with the dynamic centre of the Alaskan Gyre. Southward of the Gyre, the salinity of the waters generally decreased to a minimum (32.6–32.7‰) then increased again to southward. The minimum (centered about lat. 48°N.) was more pronounced in some years than in others.

Near the Subarctic boundary, a fairly marked meridional gradient was present marking the transition between Subarctic and Subtropic Waters. Other

areas of high salinity water (greater than 33.0‰ during the summer months) occurred in the central Okhotsk and Bering Seas. These two areas of high salinity are considered to be permanent features associated with the cyclonic circulation. Presumably the salinities are greater during winter when " freezing-out " of fresh water occurs, particularly in the Okhotsk Sea.

Off the northern Japanese islands, the salinity distribution exhibited marked gradients and irregularities which occurred in the confluence of the relatively low salinity, cold Oyashio and high salinity, warm Kuroshio. These have been smoothed considerably in the interpretation for the figures.

The most extensive oceanographic coverage during the winter months was made in the eastern Subarctic. The features of the salinity distributions were essentially the same as observed during the summer months in this area. However, during winter, the salinities appeared to be slightly greater (0.2‰) and the isohaline was closer to the coast (compare Fig. 145 and Fig. 146).

2. *Temperature at 10 metres depth.* It was difficult to obtain a complete synoptic picture of temperature at 10 metres depth in the western Subarctic and Bering Sea because there is always a progressive change of temperature during the extended period (May–September) over which the observations were made. However, the data in the eastern Subarctic were taken when the seasonal temperature changes are not significant (Fig. 41) and may be considered approximately synoptic (Fig. 151 to 158).

The configuration of the isotherms coincides with the surface circulation (Fig. 109). The isotherms lay east-west, except near the continental margins. A meridional gradient of temperature is apparent in mid-ocean.

In the Gulf of Alaska, there was usually an area of temperature minimum. In summer, this cold centre did not usually coincide with the salinity maximum associated with the dynamic centre of the Alaskan Gyre; however, in winter they were coincident. High salinity, cold water, being entrained into the upper zone, could account for the apparent relationship in these distributions and the centre of the Gyre. However, in summer, other processes must also affect the surface temperature distribution in this area.

Off the northern Japanese islands, there were several filaments of closely spaced isotherms. These indicate the distinct fronts associated with the confluence of the warm Kuroshio and cold Oyashio systems.

The pattern of winter temperature distribution was similar to that observed in summer (compare Fig. 153 and 154) although the water was about 7°C. colder. This difference is near the range observed at Ocean Station " P " (Fig. 41) and results from the uniformity of summer heating from lat. 40°N. to 60°N. (Fig. 10).

B. Bottom of Upper Zone

The bottom of the upper zone (top of the halocline) is the limit of winter convection or turnover. Within small limits of error, the salinity and temperature distributions at this level identify the isohaline and isothermal upper zone during the previous winter (Dodimead, 1961 a); thus, during summer, the temperatures at this depth are equivalent to those occurring at the period of minimum temperature during the previous winter (p. 14).

Properties at this level and at 10 metres depth adequately describe the features of the upper zone.

1. *Depth.* The depth of the upper zone varies between 50 and 275 metres, but, in general, it occurred at approximately 100 metres (Fig. 159 to 166). It was shallowest near the American coast, and this shoaling is believed to be associated with coastal upwelling which occurs in this area during summer (p. 21). In the vicinity of the Alaskan Gyre, its depth was generally less than 75 metres. This shoaling was associated with the dome (anticline of lower zone water) shown in the vertical sections.

The zone was deeper in the vicinity of the Aleutian Islands where a maximum of 275 metres was found during summer 1958 (Fig. 164). The deepening may be attributed to the considerable internal mixing due to tidal turbulence in the island passages and the zones are difficult to define.

2. *Salinity.* The salinity at the bottom of the upper zone (Fig. 167 to 174) is generally similar to that at 10 metres depth. The most saline water (33.2–33.4‰) occurred in the vicinity of the Aleutian Islands, Bering Sea and near the Subarctic boundary. Relatively saline water (33.0–33.2‰) was present in the Alaskan Gyre and usually extended westward along the southern side of the Aleutian Islands, corresponding in position to the doming of the isohalines and isotherms (p. 15).

In the eastern Subarctic there appeared to be a slight seasonal variation from winter to the following summer (compare Fig. 173 and 174) in the salinity at the bottom of the upper zone; the values were about 0.2‰ higher during summer. This behaviour is the converse of that at 10 metres depth and has been explained on page 11.

3. *Temperature.* The temperature distributions at the bottom of the upper zone are shown in Figures 175 to 182. The coldest waters were found in the Okhotsk and northern Bering Seas which are covered by ice during winter. The warmest waters occurred near the Subarctic boundary. In the eastern Subarctic, the summer distributions were similar to those that occurred in the previous winter, because heat is conserved under the seasonal thermocline (compare Fig. 177 and 178).

A tongue-like distribution of relatively cold water extended eastward from the Kuril Islands. The general increase of temperature to eastward suggests that these waters are warmed en route in the Subarctic Current by mixing with the warmer water above and below.

C. Surface of Salinity=33.8‰

The bottom of the halocline coincides closely with the isohaline surface 33.8‰. Hence, it is convenient to interpret the depth and temperature on this surface as functions of salinity rather than make the logarithmic analysis. The features on this surface adequately define the character of the water at the boundary of the halocline and lower zone.

1. *Depth.* The depths of this surface are shown in Figures 183 to 190. This surface, like the top of the halocline, also shoals in areas of upwelling and deepens in areas of mixing (tidal currents, etc.). The surface generally occurred at depths between 175 and 225 metres, but in some areas, it was found at depths as shallow as 150 metres (Alaskan Gyre) and as deep as 500 metres (Okhotsk Sea). In the Bering Sea, the depth was generally greater than 250 metres, the shallowest depths being near the continental shelf.

2. *Temperature.* Fleming (1958) pointed out the marked similarity in temperature distribution on the surface of salinity=33.77‰ and the geostrophic circulation at the 200 decibar level during summer, 1956. From a comparison of Figures 191 to 198 (temperature distribution on the surface of salinity=33.8‰) and Figures 110 to 117 (geostrophic circulation at 200 decibars) it is obvious that there is a marked similarity except off the Washington-Oregon coasts where the computed flow was northward, opposite to that implied by the isotherms.

A tongue of cold water extended eastward from the Kuril Islands. A similar feature was evident in the temperature distribution at the bottom of the upper zone. The general increase of temperature to the eastward suggests that, since this water has no contact with the surface, the warming must be due to advection of warmer water, presumably from the south, the only source of such water. Southward of this tongue in the western and central Subarctic there was a marked meridional gradient. The isolated cold areas south of the Aleutian Islands and in the Gulf of Alaska mark the peaks of the anticline in the sub-halocline structure. Over most of the Bering Sea, the temperatures of these waters varied between 3.5°C. and 3.75°C.

D. Surface of Salinity=34.0‰

The surface of salinity=34.0‰ lies well within the lower zone and, thus, is considered to represent its character to approximately 1000 metres depth. Near the Subarctic boundary where the occurrence of a salinity minimum results in the presence of two surfaces of salinity=34.0‰, the deeper surface is used. Water at and below this level is continuous with that in the Subtropic Region.

1. *Depth.* Figures 199 to 206 show that shallowest depths (less than 250 metres) occurred in the area of the anticline (associated with the Alaskan Gyre) and its extension along the Aleutian Islands. In some years, the shallow depths in this area do not appear to be continuous suggesting a circulation of the lower zone waters southward into the mid-ocean area where they may be absorbed in the eastward flow. Between the anticline and the Aleutian Islands, the depth of this surface increased markedly to approximately 500 metres. Southward of the anticline, the downward slope of this surface extended southward of the Subarctic boundary. Near the North American coast the surface shoaled to approximately 200 metres depth.

The greatest depths were present in the Okhotsk Sea (greater than 800 metres) and on the eastern side of the Kuril Islands indicating that vertical mixing occurred to greater depths in this area than in other parts of the Subarctic. In the eastern Bering Sea, the surface extended to depths greater than 500 metres.

2. *Temperature.* The distributions of temperature on the surface of salinity=34.0‰ (Fig. 207 to 214) show that the coldest water (1°C. to 2°C.) occurred in the Okhotsk Sea, suggesting that these waters originated at the surface as a result of extreme cooling and subsequently were mixed downward to these depths. Too, the unique temperature and salinity structures (Fig. 34) indicate that there is a very small exchange of water at these depths between the Pacific Ocean and Okhotsk Sea. Evidently it can be considered an almost isolated body of water. Some outflow from the Okhotsk Sea is noted by the presence of low temperatures, on the eastern side of the Kuril Islands.

A tongue of relatively cold water which occurred as a temperature minimum was confined to the area north of lat. 45°N. and south of the anticline along the southern side of the Aleutian Islands, and was not associated with the doming of the isohalines and isotherms. Instead, this water, like the overlying waters, was associated with the eastward flowing current. As this water moves eastward, it warms, and loses its characteristic temperature (less than 3.75°C.) in the Gulf of Alaska.

In sharp contrast to this cold water, a tongue of warm water apparently intruded northward along the North American coast. Its seaward boundary is marked by an appreciable gradient and appears to result from a convergence of the subsurface eastward and northward flows. Its northern boundary extended to the coast of British Columbia, but was less distinct.

Over most of the Bering Sea, the temperatures on this surface were between 3.5°C. and 3.75°C. and thus were similar to those at the surface of salinity = 33.8‰. In this area, the lowest temperatures were found in the eastern and northern Bering Sea.

VII. DOMAINS

The usual method of identifying unique features of an area or region is by temperature-salinity relationships which define water masses. In this manner, Sverdrup *et al.* (1942) have identified Subarctic and Central Pacific Water which are distinct. More recently, numerous attempts have been made to subdivide Subarctic Water by this method (Hirano, 1958; Dodimead, 1958; Kitano, 1959; Favorite and Hebard, 1961). The net result of all these studies is a fan of curves as illustrated in Figure 215, defining a gradation of properties which are arbitrarily subdivided. The definitions in this sense are inconclusive. From the previous discussions, the unique feature of the Subarctic is the salinity-zone structure. Distributions of temperature and salinity have been discussed on significant surfaces deduced from the salinity-zone structure; e.g., 10 metres, bottom of upper zone and salinity surfaces of 33.8‰ and 34.0‰. From these distributions, it is possible to define " domains " in the Subarctic, and this approach has been adopted in the section.

The concept of a domain contains the ideas of consistent properties, structure, behaviour (flow, heating and cooling, etc.), climatic locality and continuity. It does not depend on any one of these, which might occur in widely separated localities, but on a rational consistency in all aspects. Also, it is possible to use any convenient index or combination to define the extent of the domains and this makes it possible to summarize the variations that have occurred. Specific domains have been identified in the upper zone where the properties of the water are predominantly influenced by such factors as seasonal heating and cooling, precipitation, evaporation and wind mixing; and in the lower zone where the properties of the water are predominantly affected by internal processes such as advection, diffusion, etc. The halocline represents the transition from the upper to the lower zone domains.

A. Upper Zone Domains

Figure 216 shows five principal domains, based on their temperature and salinity and flow characteristics, that are identified in the upper zone—(1) *Western Subarctic*, (2) *Transitional*, (3) *Alaskan Stream*, (4) *Central Subarctic*, and (5) *Coastal*.

1. *Western Subarctic Domain.* The general characteristics of this domain are:

(a) The temperature structure at all times exhibits a cold subsurface minimum at the bottom of the upper zone.

(b) The depth of the upper zone is between 100 and 150 metres.

(c) Relatively high salinity water prevails; generally between 33.0 and 33.2‰ in the surface waters in the Bering and Okhotsk Seas and slightly lower values (32.6–33.0‰) in the remainder of the domain. Near the bottom of the upper zone, salinities are between 33.0 and 33.4‰.

(d) Within this domain, three cyclonic gyres are present; the Bering Sea, Western Subarctic and Okhotsk Sea. Other features of the circulation are the East Kamchatka and Oyashio Currents.

The extent of this domain can be adequately defined by temperatures less than 3.5°C. at the bottom of the upper zone.

2. *Transitional Domain.* This domain lies just north of the Subarctic boundary. The general characteristics are:

(a) The flow is principally zonal, except near the North American coast. There it veers northward and southward.

(b) Surface waters are warm (warmer than 15°C. in summer and 7°C. in winter).

(c) Relatively high salinity water occurs throughout most of the domain; greater than 33.2‰ in the surface waters and greater than 33.4‰ near the bottom of the upper zone. However, east of long.

150°W. dilution of these waters occurs.

(d) A subsurface minimum temperature at the bottom of the upper zone may be present.

(e) Marked meridional gradients of temperature and salinity occur.

The northern edge of this domain can be identified by the 7°C. isotherm at the bottom of the upper zone.

3. *Alaskan Stream Domain.* This domain is associated with the relatively dilute warm water which flows out of the Gulf of Alaska westward along the southern side of the Aleutian Islands and is considered to begin at about the longitude of Kodiak Island where the flow narrows and accelerates. Coastal water is also present in the Alaskan Stream but is modified by the considerable mixing due to the strong tidal currents along the Islands and through the passages.

Variations in the extent of this domain can be deduced from the distribution of surface water less than 32.6‰ and the relatively warm water in the vicinity of the Aleutian Islands.

4. *Central Subarctic Domain.* This domain lies within the boundaries of the Western Subarctic, Transitional, Alaskan Stream and Coastal Domains. The general characteristics of this domain are:

(a) One cyclonic gyre (Alaskan Gyre) is present.

(b) The depth of the upper zone extends to approximately 100 metres except in the Alaskan Gyre where it shoals to approximately 75 metres.

(c) The salinity of the upper zone is 32.4 to 32.8‰ in the surface water and 33.2 to 33.4‰ near the bottom of the upper zone.

(d) A salinity maximum occurs in the Alaskan Gyre.

(e) The temperature structure may exhibit a subsurface minimum at the bottom of the upper zone. However, the dichothermal structure may occur only in parts of the domain.

5. *Coastal Domain.* The oceanographic features of this domain vary markedly from one area to the other, because of the local variations in runoff, heating and cooling, winds, tides and advection; thus, the properties, structure and dynamics of the waters are variable. There may be strong tidal currents which cause considerable mixing, hence the ocean halocline structure is modified and in some areas it vanishes. Upwelling may occur in many localities when the winds are suitable. Because of these and other factors, mechanisms are sometimes difficult to define. The known features and mechanisms have been summarized in the Appendices which define conditions in specific coastal areas. These now need to be applied to other coastal areas before the features of this domain can be fully summarized.

The extent of this domain can be defined by the isohaline of 32.4‰ in the surface waters (at 10 metres depth). In summer, when this surface lens of dilute water intrudes into the oceanic areas an overlap in the boundaries of this and other domains occurs.

6. *Variations, 1955 through 1959.* Specific domains in the Subarctic associated with the upper zone have been established. Now it is possible to discuss their relationships to one another and relate the sequence of events that have occurred each year.

The extent of the five domains for each year are shown in Figures 217 to 224. One of the most obvious features is the westward and southward extent of the Alaskan Stream. This domain extended further offshore during 1955 and 1958 than in the intervening years, suggesting a fairly pronounced southward component in the circulation of the Alaskan Stream at least in the upper zone.

Although the main body of this water moves westward and then northward through the Aleutian passages, it is evident that a portion of it is dissipated southward into the Central Subarctic Domain. Also this dissipation evidently occurred at different locations along the southern side of the Aleutian Islands, resulting in variations in the salinity of the water south of the Alaskan Gyre in the Central Subarctic Domain. The presence of cells of relatively low salinity water, within this salinity minimum, suggests that this dissipation may be intermittent.

The westward extension of the Alaskan Stream Domain was least during summer 1955. During summer, 1956 and 1958, the westward extension of water less than 32.6‰ was furthest (compare Fig. 143, 144, 146, 148 and 150). In 1958, there was an apparent increase in the amount of water flowing into the Gulf of Alaska and hence into the Alaskan Stream, resulting in a westward extension of warm dilute water associated with the Alaskan Stream and slightly lower salinities in the central Bering Sea than in other years. An increased flow was not apparent in 1956. However, it is possible that the dissipation through the Aleutian passages was small, as evidenced by the slightly higher surface salinities in the Bering Sea; thus, most of the water flowed westward, resulting in a westward extension of the dilute warm water in summer 1956.

Favorite (1961) reported on the variations of surface salinity off the coast of British Columbia, showing that in 1958 the coastal waters (Coastal Domain) extended

further offshore than in 1959. This appears to be related to the circulation pattern, which has been shown to be more northerly in the offshore areas during 1958 than in the other years, and which apparently allowed an offshore movement of the coastal waters. At the same time in the northeastern part of the Central Subarctic Domain, low salinity water occurred.

In contrast to the distribution of low salinity water in the eastern Subarctic, the coastal waters in the eastern Bering Sea did not extend as far off the continental shelf in 1958 as in other years. It has already been suggested that the flow of the Alaskan Stream was greater during 1958 and flow into the Bering Sea was proportionately larger. This would result in an increased flow to the eastward, north of the Aleutian Islands, and a confinement of the Coastal Domain to a narrower band than in the other years.

Off the North American coast, the Coastal Domain did not extend as far seaward in winter as during summer. This may be attributed to intensified vertical mixing and reduced supply of fresh water from land drainage and/or seasonal changes in the offshore circulation. In summer 1959, the Coastal Domain water appeared to be discontinuous along the coast of Vancouver Island; apparently marked upwelling occurred during this period.

The most obvious variation in the extent of the Transitional Domain occurred off the coast of British Columbia. During 1957, this domain moved northward along the coast and reached its furthest extent in 1958. By winter 1959 it had retreated, but not to the position observed in the earlier years.

It appears that a northward shift in the position of the Transitional Domain in the eastern Subarctic was accompanied by an eastward and southward expansion of the Western Subarctic Domain in 1958. The next year, 1959, the eastward extent of the Western Subarctic Domain was furthest, but was not continuous and the easterly extremity occurred as a cell in which the water was not as cold as observed in 1958. This cell was probably a remnant of the water that was present in 1958 near this area.

Variations in the Central Subarctic Domain were most apparent in the Gulf of Alaska. Temperatures at the bottom of the upper zone in the Alaskan Gyre were lowest in 1956 (less than 3.0°C.), being as low as water associated with the Western Subarctic Domain and were evidently generated locally as a result of marked cooling. In 1957 surface temperatures in the northern Gulf of Alaska were high and did not appear to be a result of advection. It appears that marked heating occurred during summer 1957.

The highest surface salinities in both winter and summer in the Central Domain were associated with the centre of the Alaskan Gyre, the area of maximum shoaling of the isohalines. Only in winter did the low surface temperatures appear to be associated with this centre (see p. 22).

B. Lower Zone Domains

Four principal domains which extend to at least 1000 metres depth are identified (Fig. 225)—(1) *Western Subarctic*, (2) *Transitional*, (3) *Central Subarctic*, and (4) *California Undercurrent*. Because of the similarity in flow in the upper and lower zones, these domains, in general, underlie those identified in the upper zone, but in the lower zone a new domain, the California Undercurrent, is found.

1. *Western Subarctic Domain.* The source of this water is principally the Bering Sea. This water flows southward along the coast of Kamchatka, is modified by waters from the Okhotsk Sea and then moves principally eastward into the Gulf of Alaska. However, some of this water extends south of the Subarctic boundary in the Oyashio Undercurrent off the coast of Japan.

This domain can be adequately defined by a temperature lower than 3.75°C. on the surface of salinity =34.0‰.

2. *Transitional Domain.* This domain lies near the Subarctic boundary. The flow of water is principally eastward, but near the North American coast it veers northward and then southward. In the western and central Subarctic, the domain is narrow and is characterized by marked meridional gradients. In the eastern Subarctic it broadens and gradients become less pronounced. The extent of this domain has been identified by a temperature of less than 6.5°C. at the surface of salinity=33.8‰.

3. *Central Subarctic Domain.* This domain represents a large portion of the oceanic Subarctic. The waters overlying this domain are characterized by the well defined halocline which is maintained by the recirculation of the relatively dilute surface waters. Associated with this domain is the Alaskan Gyre. It exists below 200 metres depth and is identified by a temperature between 3.75°C. and 6.0°C. on the surface of salinity=34.0‰ and is continuous with water below the salinity minimum in the Subtropic Region.

4. *California Undercurrent Domain.* This domain is associated with northward flowing lower zone waters and is bounded by a marked latitudinal gradient of temperature. It can be identified by temperatures

greater than 6.0°C. on the surface of salinity=34.0‰ but cannot be identified at the shallower level of 33.8‰. The source of this water appears to be south of lat. 35°N. in the eastern boundary region of the Subtropics.

5. *Variations, 1955 through 1959.* The extents of these domains for each period, 1955 through 1959, are shown in Figures 226 to 233. Tully *et al.* (1960) have described the changes in these non-seasonal waters along the coast of British Columbia using temperature on a constant density surface (σ_t=26.60) occurring near the bottom of the halcoline. Tully and Barber (1960) compared these isopycnal and halocline (temperature on the surface of salinity=33.8‰) analyses and showed that they coincided in every principal feature. In these studies, it was concluded that there was a progressive northward intrusion of the Transitional Domain along the British Columbia coast in the period 1955 through 1958 (Fig. 225 to 230). Apparently this domain intruded furthest during early 1958. Data to 1962 show that it has not retreated to the position observed in 1957 and earlier. Uda (1962) compared similar occurrences off the coast of Japan as reported by Uda (1960) and Takenouti (1960). By contrast with the sequence off the Canadian coast, the order of the warm water intrusions was 1955 (strongest), 1956, 1957 and 1958 (weakest), just the reverse of conditions off the Canadian coast. Thus it appears that when cold conditions exist off the coast of Japan, warm conditions may be found off the Canadian coast.

Recently Dodimead (1961b) discussed this Transitional Domain and showed that in the eastern Subarctic it was furthest north in 1958 and 1959. At the same time the area of divergence of the dynamic isopleths at this level was furthest southward (see Circulation, p. 19). These are separate phenomena. The final result is that more warm water moved northward along the British Columbia coast resulting in anomalous conditions, both in the properties of the waters and the circulation along the British Columbia coast. In 1959, the northward limit of the boundary was similar to that in 1958; however, the area of divergence had shifted northward in 1959. Therefore, less warm water flowed northward in 1959 than in 1958. He also suggested that an increase in the strength of the northward subsurface flow (California Undercurrent) would result in warm water intruding at depth along the British Columbia coast. Therefore, it is possible that the variations in the position of this Transitional Domain may be generated, at least in part, in the deeper sub-halocline waters. Evidently there are three dynamic causes of climate in the region of division of the West Wind Drift.

There appears to have been a progressive eastward shift in the Western Subarctic Domain (Fig. 226 to 233), similar to the eastward shift of this domain in the upper zone. It reached its maximum eastward extent (long. 142°W.) in summer 1958 (Fig. 231) and remained in the same position during 1959. This water moves from the Bering Sea to the vicinity of the southern Kuril Islands and then principally eastward. It is warmed en route, finally mixing with the northward flowing waters in the Gulf of Alaska. From here, it moves westward in the Alaskan Stream; however, the characteristic temperature has been altered. In years when the Western Subarctic Domain appears to have its maximum eastward extent, its southern extent off the coast of Japan is least.

The seaward extent of the California Undercurrent also varies. It extended furthest offshore in 1959 and was confined to a very small area in 1956.

VIII. SUMMARY

This review describes:

(1) The Subarctic boundary. It extends across the ocean from Asia to America and is a recognizable boundary between the Subarctic and Subtropic waters.

(2) The Subarctic salinity structure. There is a permanent halocline maintained by an excess of precipitation over evaporation with a brackish upper zone above it, and a saline lower zone below. This feature defines the Subarctic Region and salmon water.

(3) Surface heating, cooling and wind-mixing processes and the consequent features of growth and decay of the seasonal thermocline. From these it is possible to assess and present the near-surface temperature structure, and assess the temperature in the upper zone during the previous winter from data observed during the summer.

(4) The circulation systems. The several currents and gyres have been named, as well as the relationship with the Subtropic circulation. Comparison of geostrophic transports from hydrographic data and wind stress transports from meteorological data show that there is a possibility of predicting the transport of water within specific areas.

(5) The concept of domains within the Subarctic Region. Domains are areas of consistent structure and oceanographic behaviour. This replaces the classical concept of water masses which are not definitive in the Subarctic.

The immensity of the field work that has been accomplished since 1955 should be obvious, and the fact that it is a particularly successful cooperative marine

investigation is unquestionable. As a result, this Region has advanced from one of the least known to one of the best known oceanic regions. It is also encouraging to point out field work has continued up to the time of this report, and further discoveries and refinements of our present knowledge can be expected in the near future. But perhaps equally important is the fact that extensive salmon fishing has been carried out during the course of these investigations, and that the results of the oceanographic work are beginning to shed some light on the distribution and migration of the salmons while in the oceanic environment.

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FIGURE 124. Geopotential topography, 500/1000 decibars, summer 1958.
FIGURE 125. Geopotential topography, 500/1000 decibars, winter 1959.
FIGURE 126. Geopotential topography, 500/1000 decibars, summer 1959.
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FIGURE 207. Temperature on the surface of salinity=34.0‰, summer 1955.
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FIGURE 210. Temperature on the surface of salinity=34.0‰, summer 1957.
FIGURE 211. Temperature on the surface of salinity=34.0‰, winter 1958.
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FIGURE 230. Lower zone domains, winter 1958.
FIGURE 231. Lower zone domains, summer 1958.
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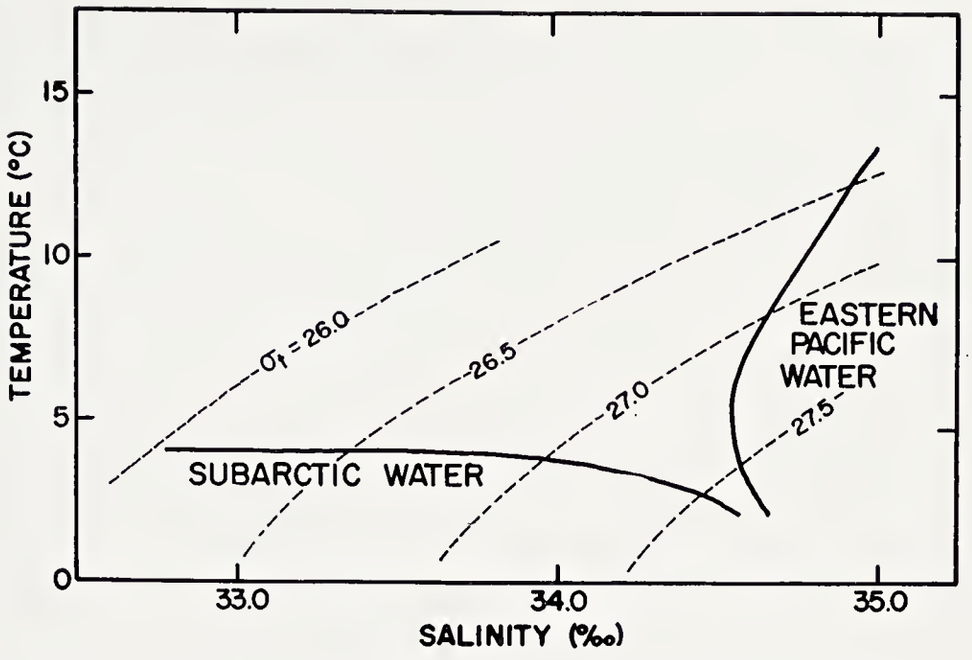


FIGURE 1. Representative T-S curves of Subarctic and Eastern Pacific Waters.

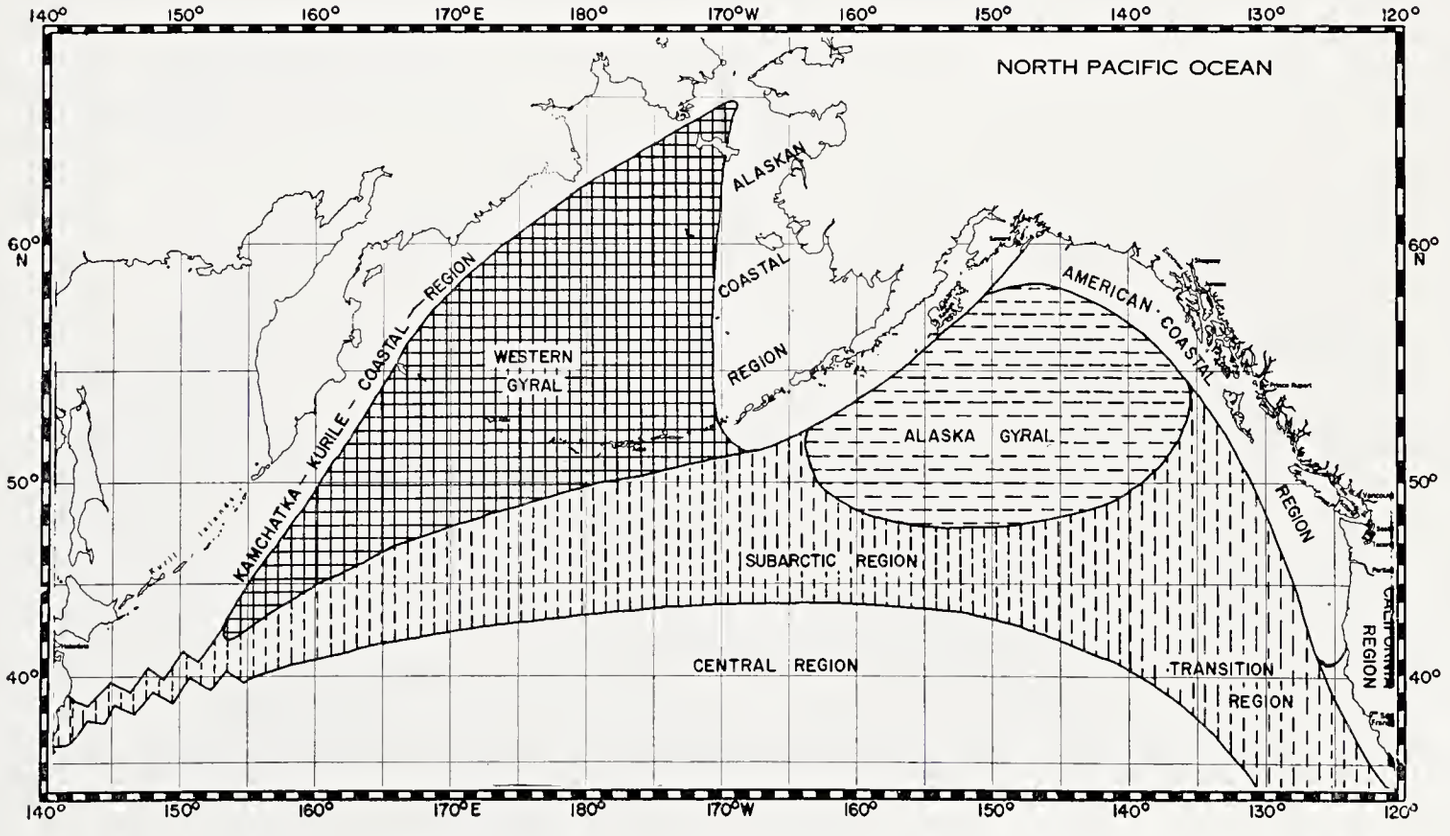


FIGURE 2. Regions and zones in the northern Pacific (adapted from Fleming, 1955).

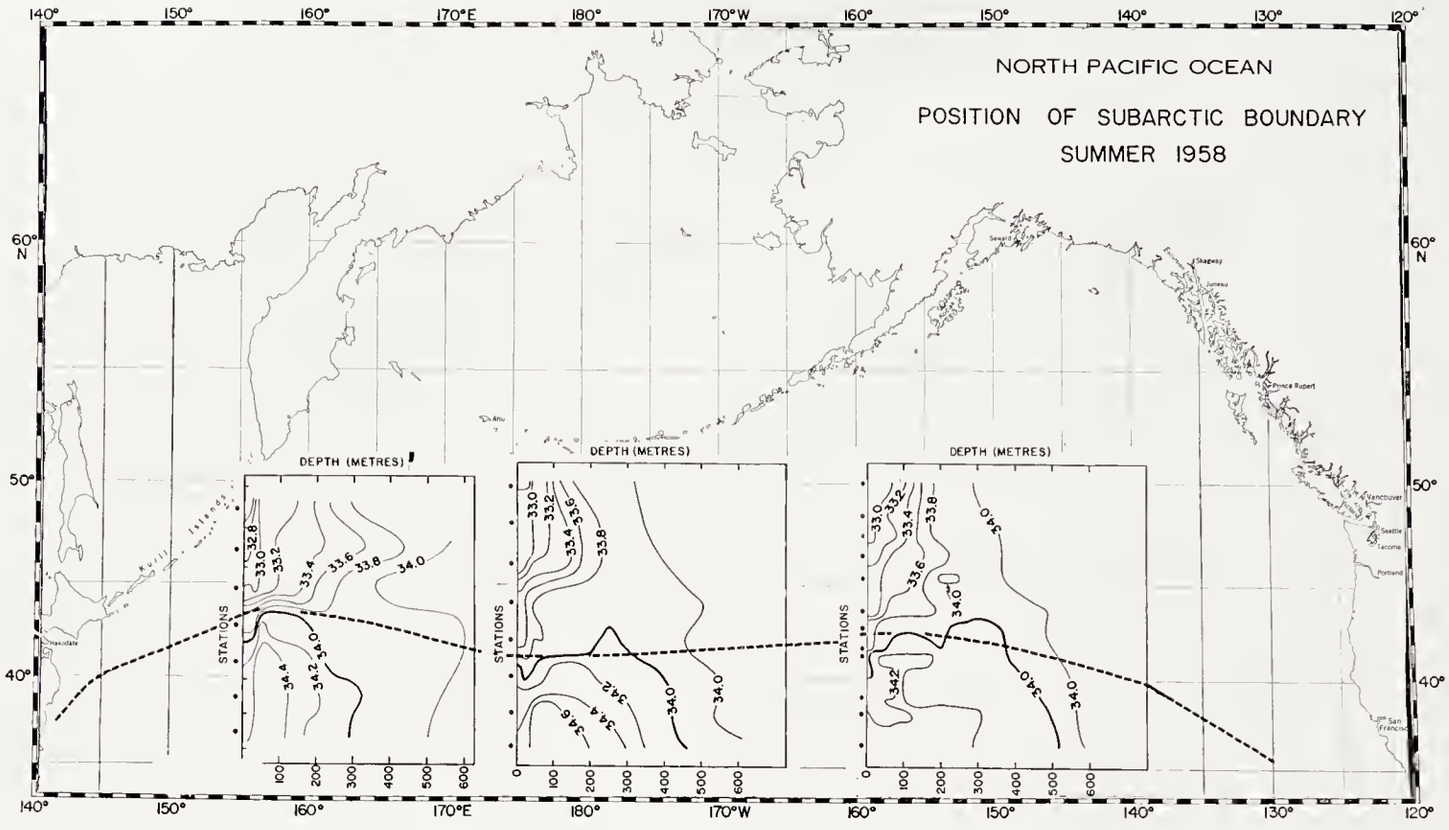


FIGURE 3. Position of Subarctic boundary during summer 1958.

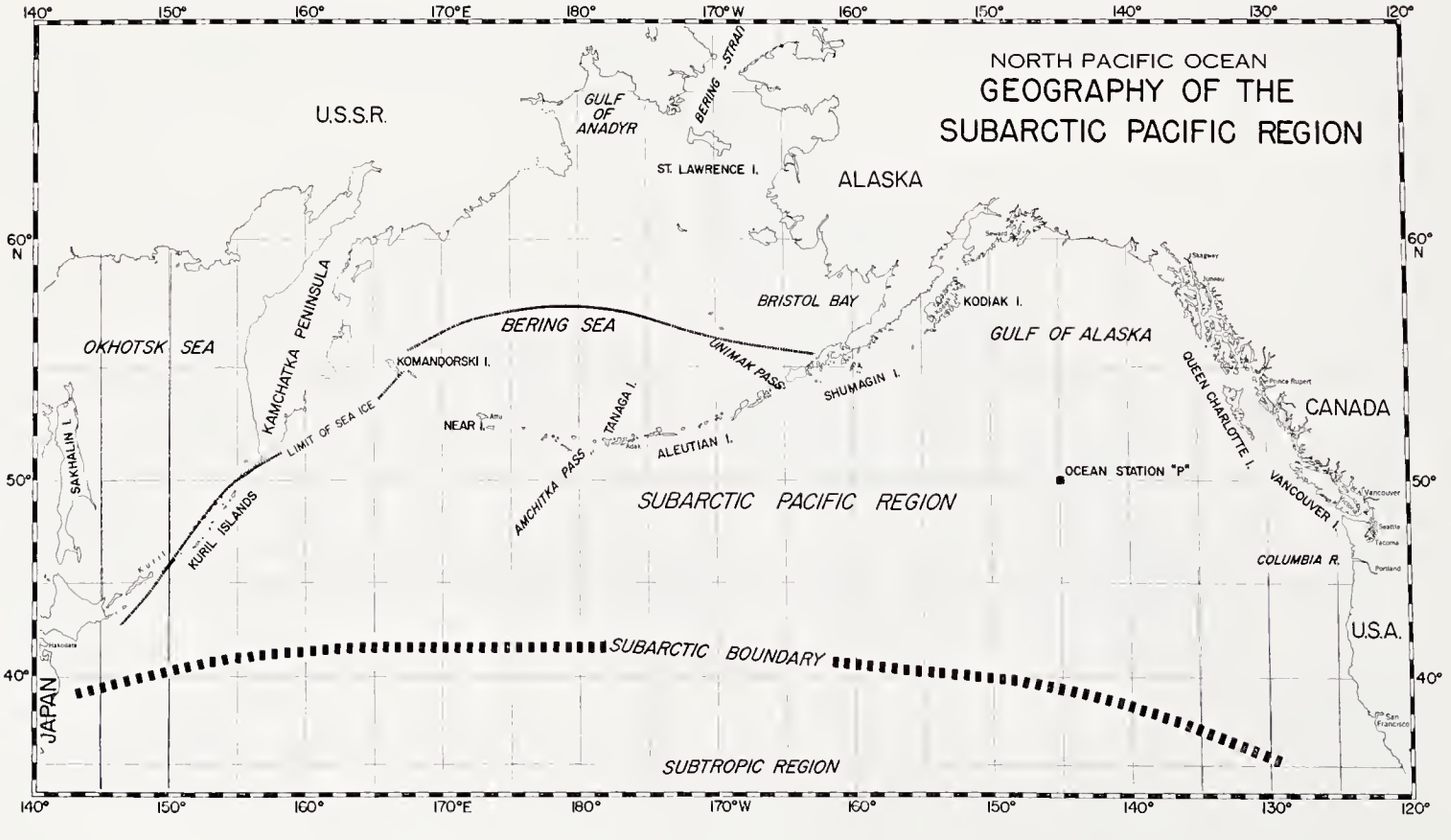


FIGURE 4. Geography of Subarctic Pacific Region.

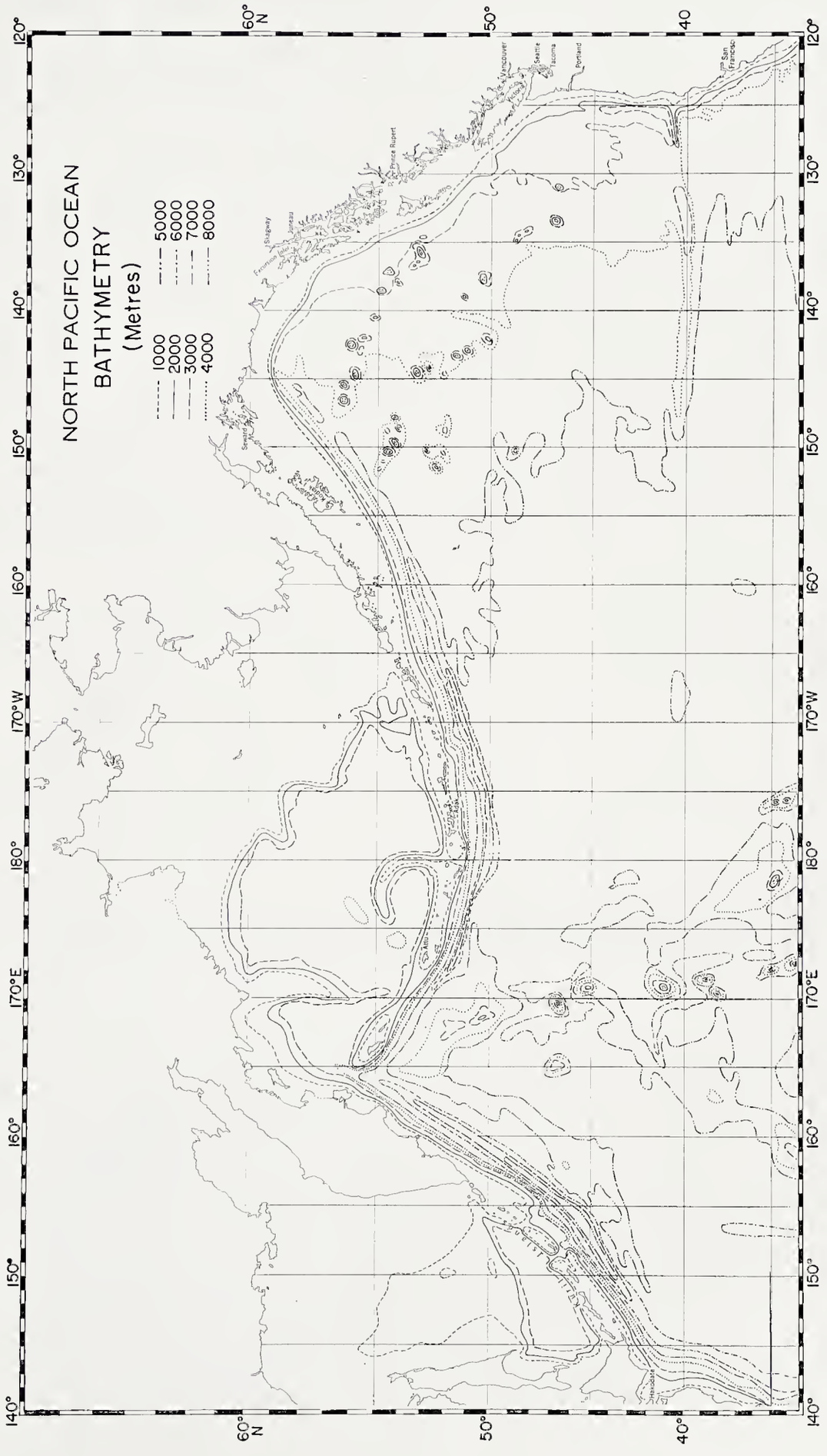


FIGURE 5. Bathymetry (metres).

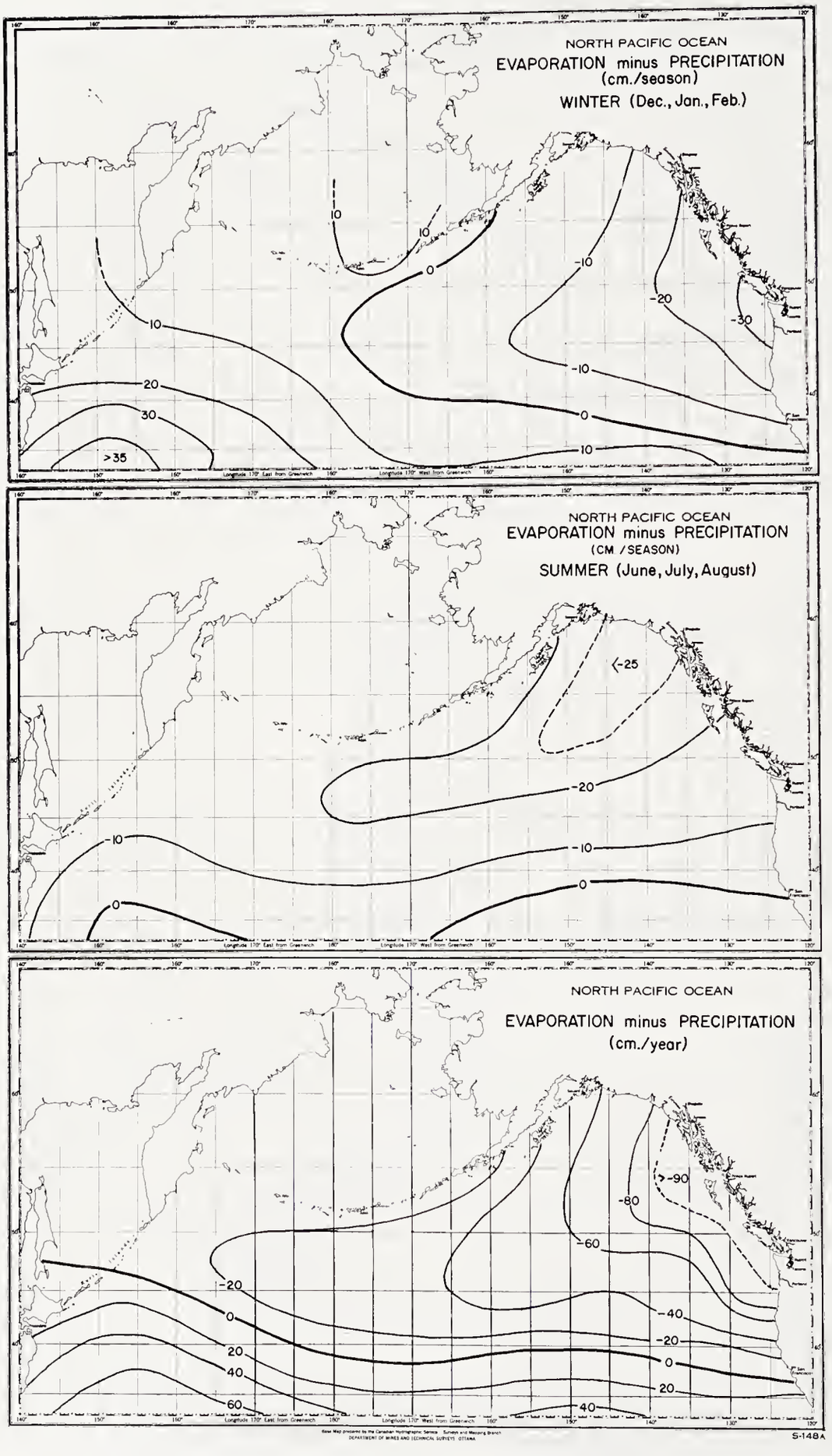
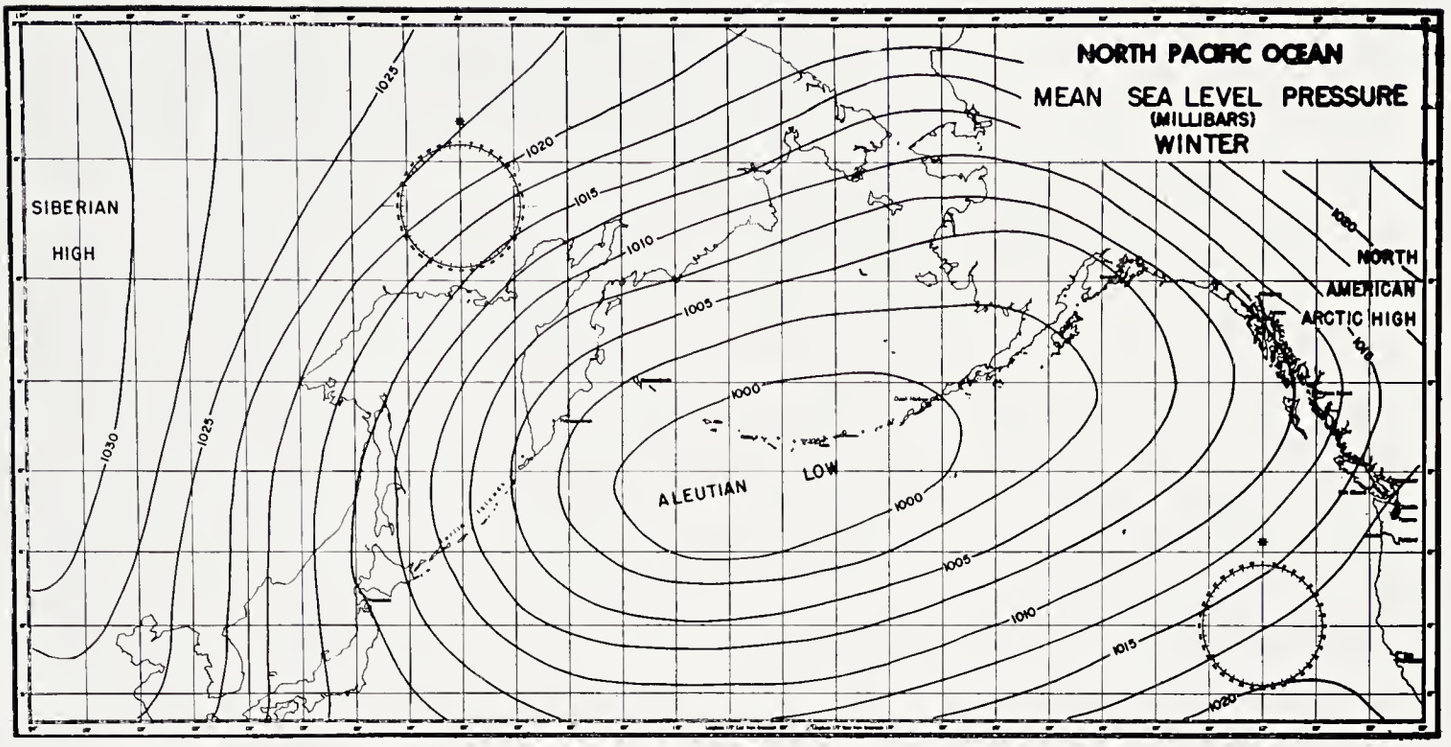


FIGURE 6. Evaporation minus precipitation—winter, summer and annual conditions (adapted from Jacobs, 1951).



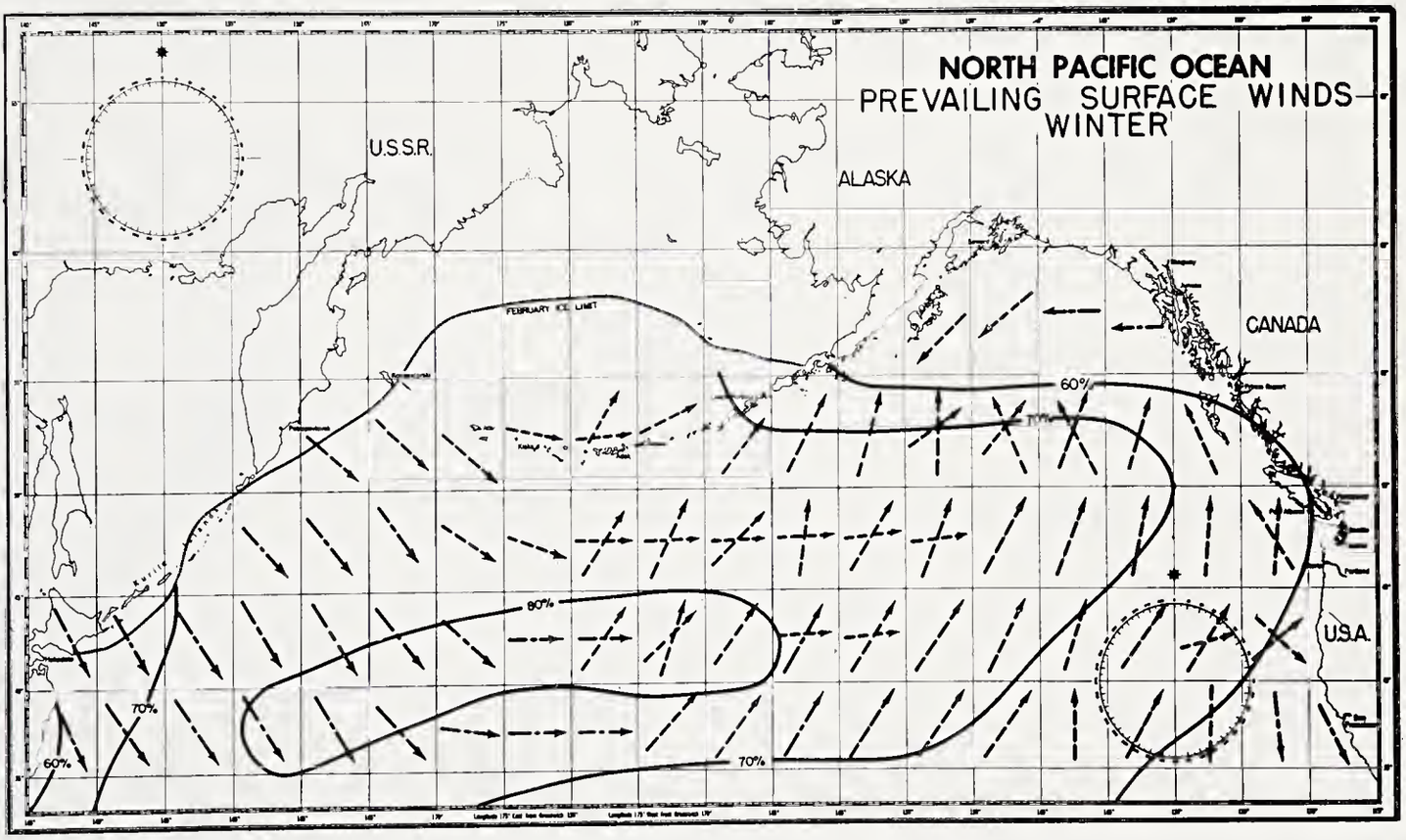
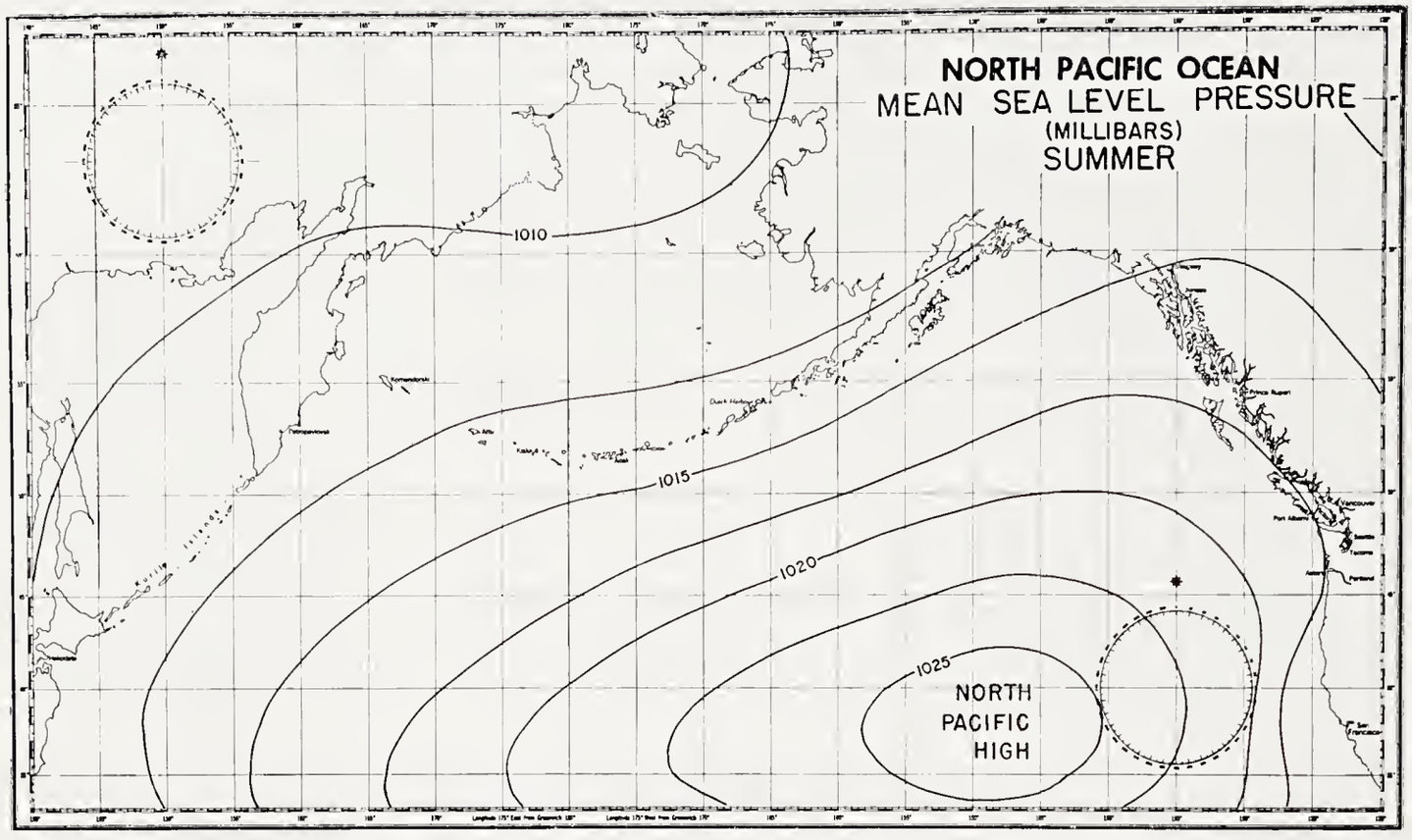


FIGURE 7. Mean sea level pressure (millibars) and prevailing surface winds during winter (contours indicate the percentage of time the winds are Force 3 and less).



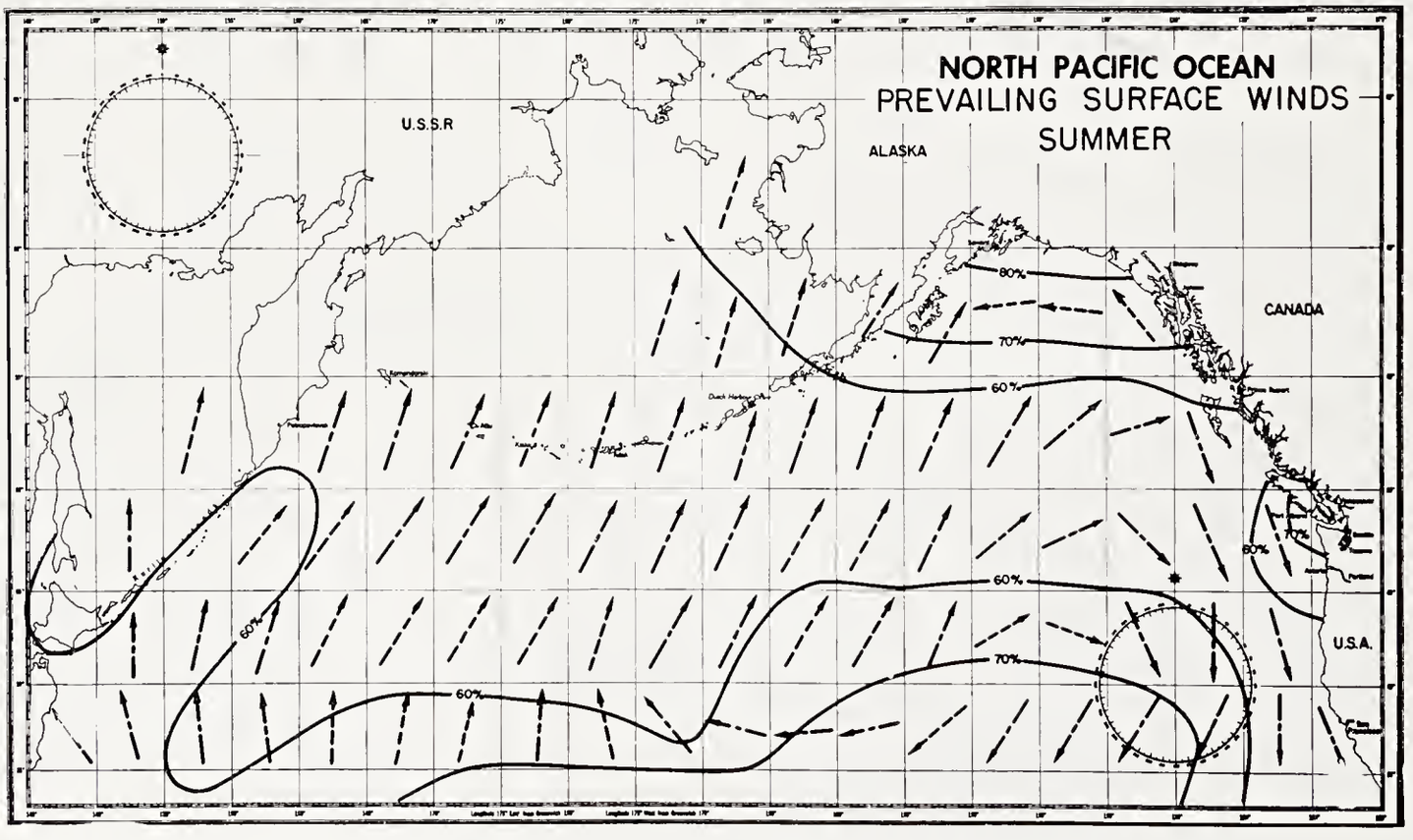


FIGURE 8. Mean sea level pressure (millibars) and prevailing surface winds during summer (contours indicate the percentage of time the winds are Force 3 and less).

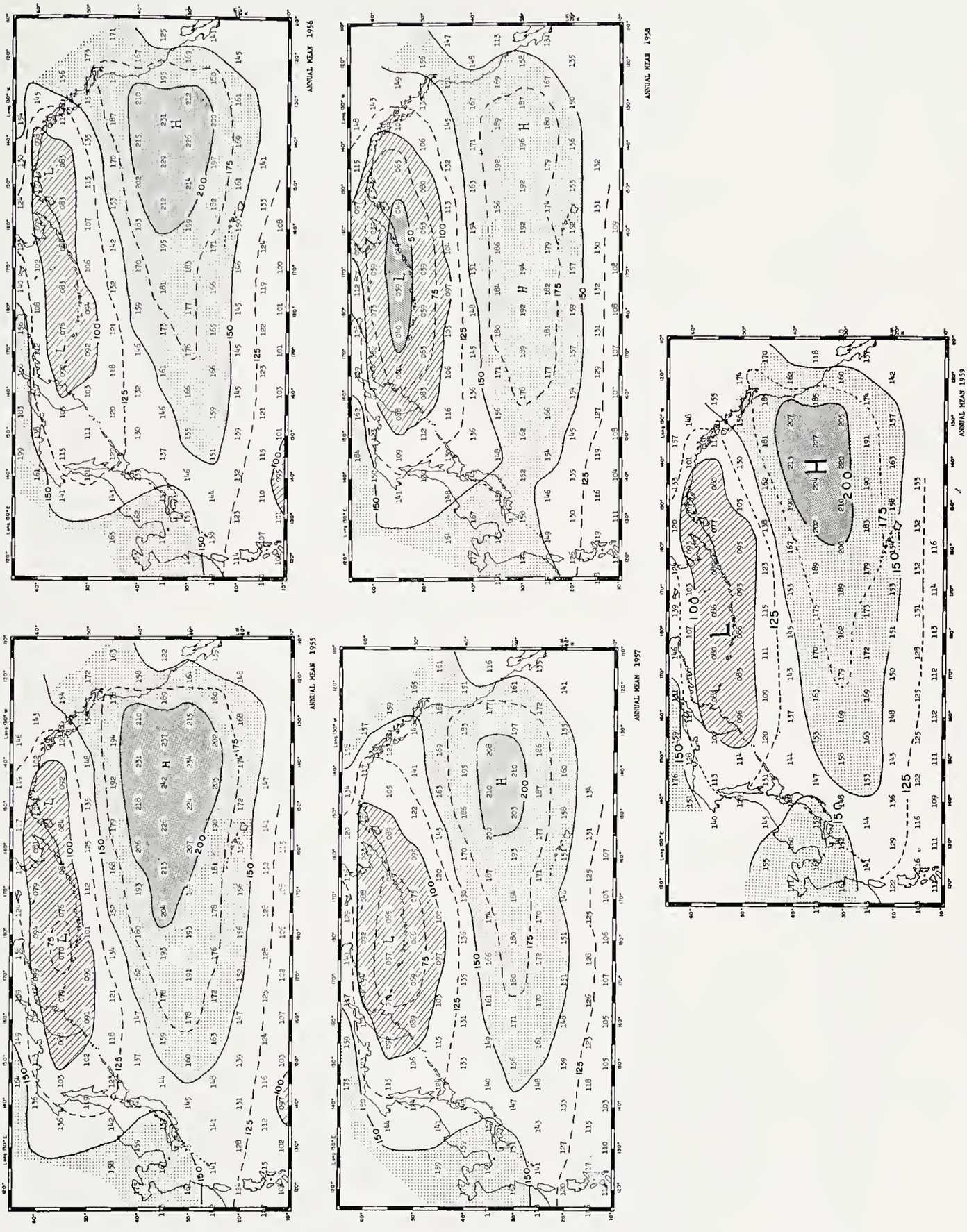


FIGURE 9. Annual mean sea level pressure, 1955 to 1959.

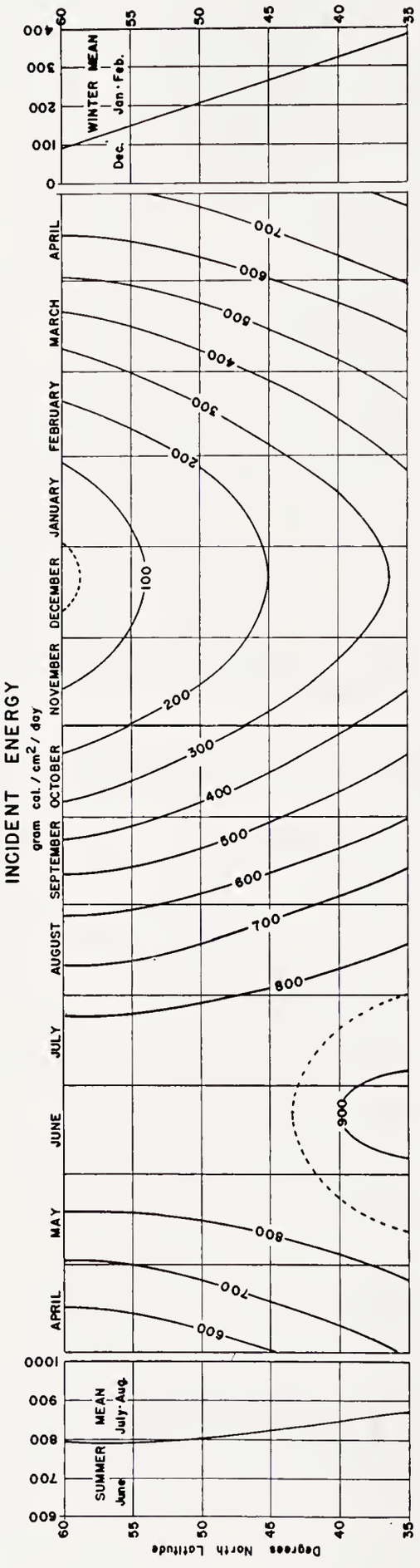


FIGURE 10. Annual cycle of incident energy (gram cal/cm²/day) from lat. 35°N. to 60°N. (Tully and Dodimead, 1957).

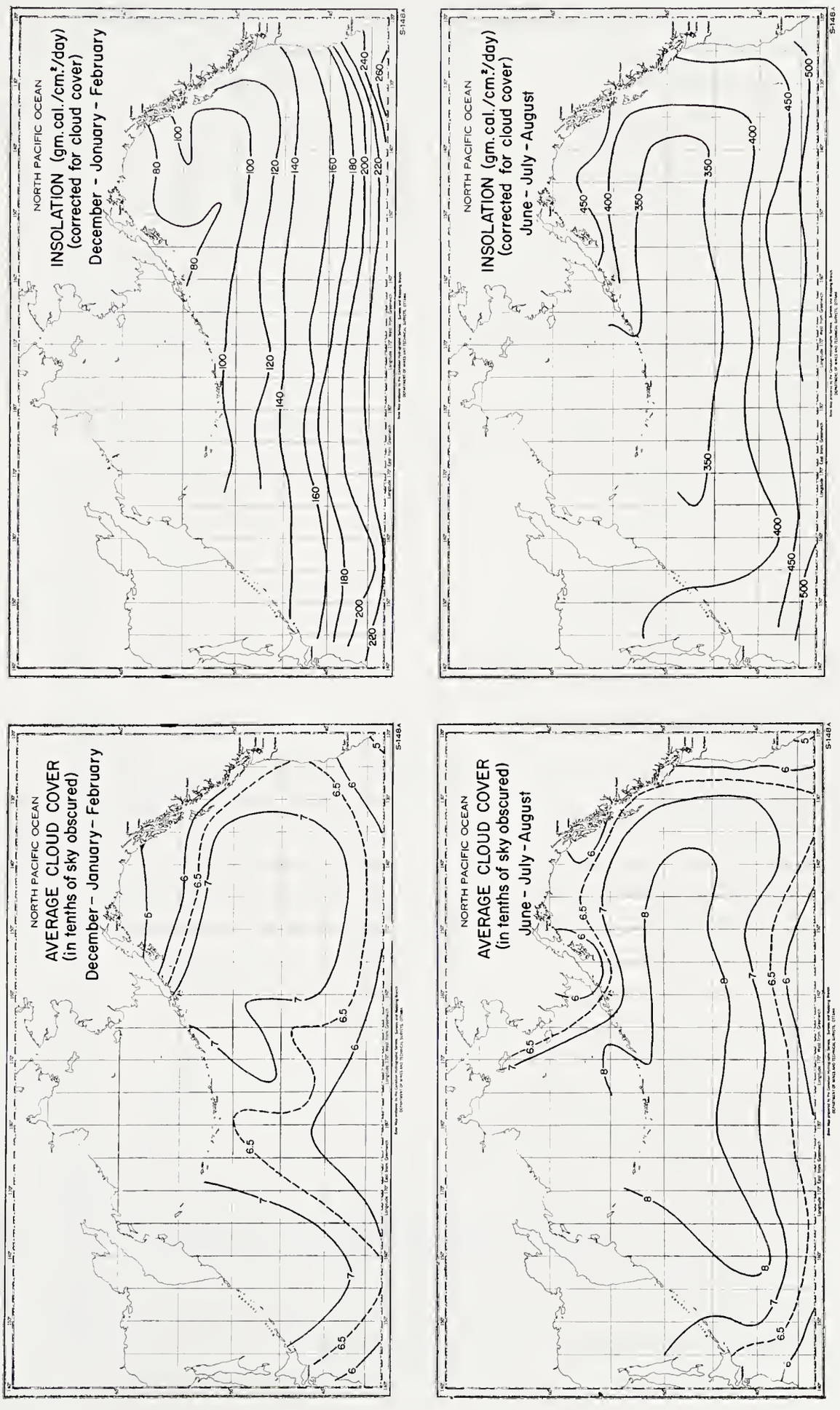
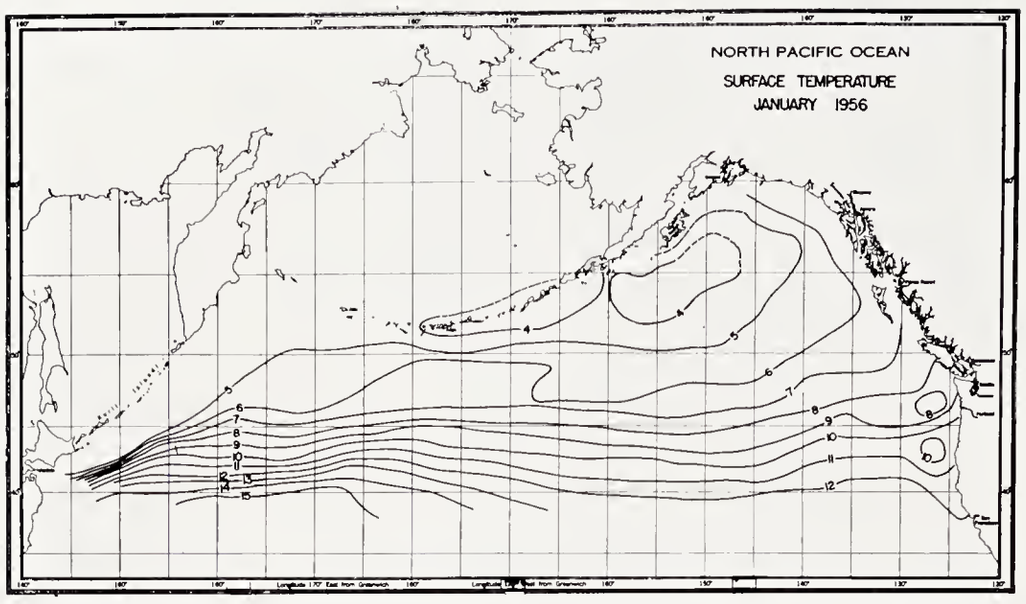
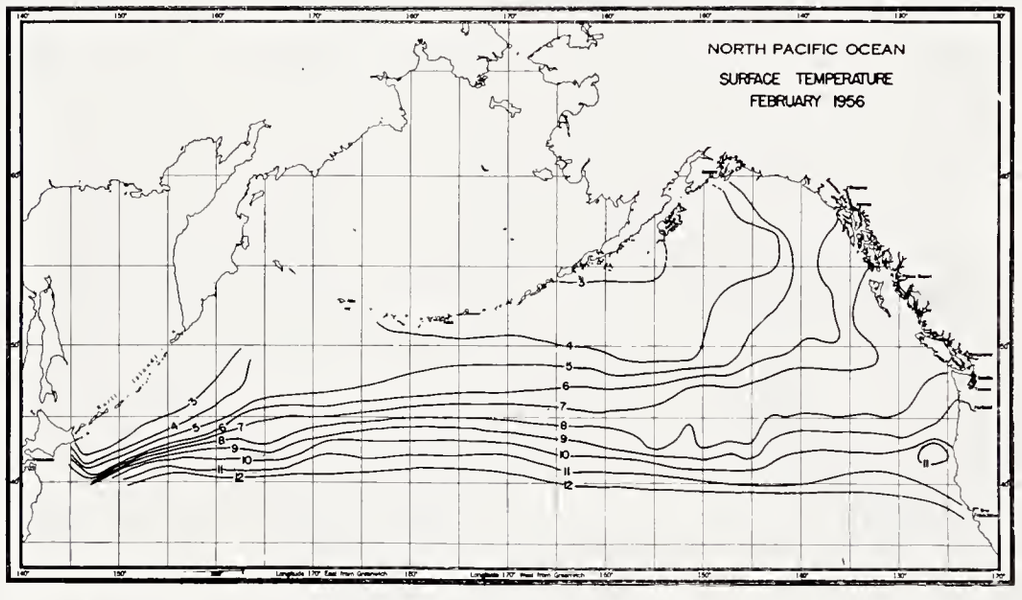


FIGURE 11. Average cloud cover and insolation during winter and summer.





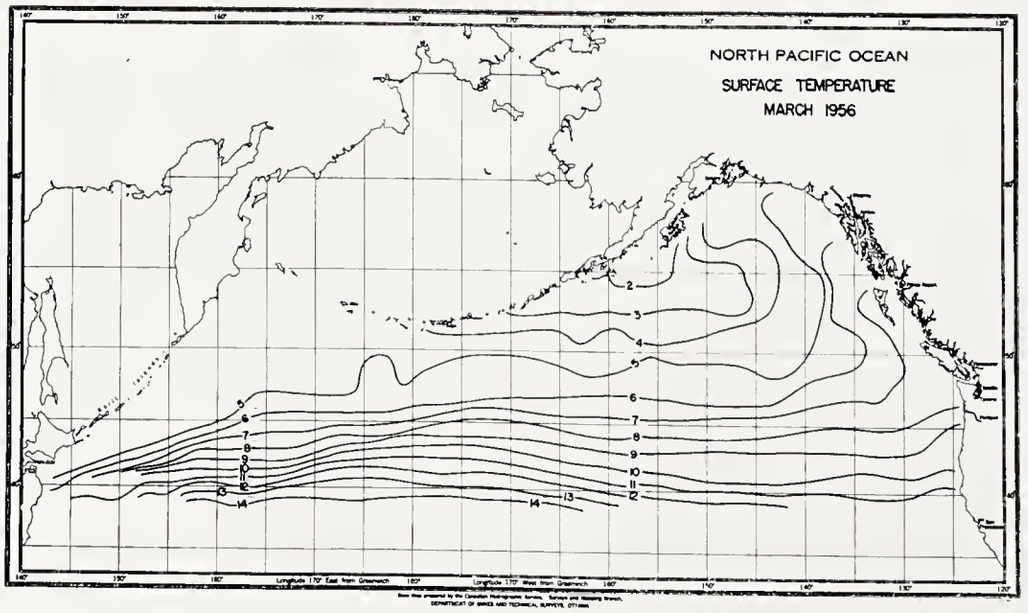
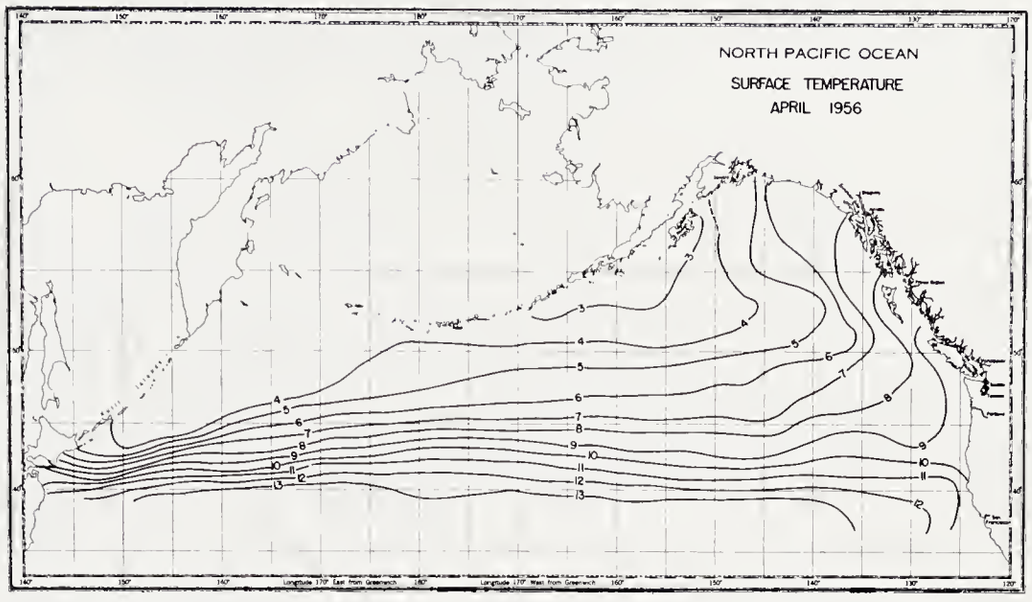
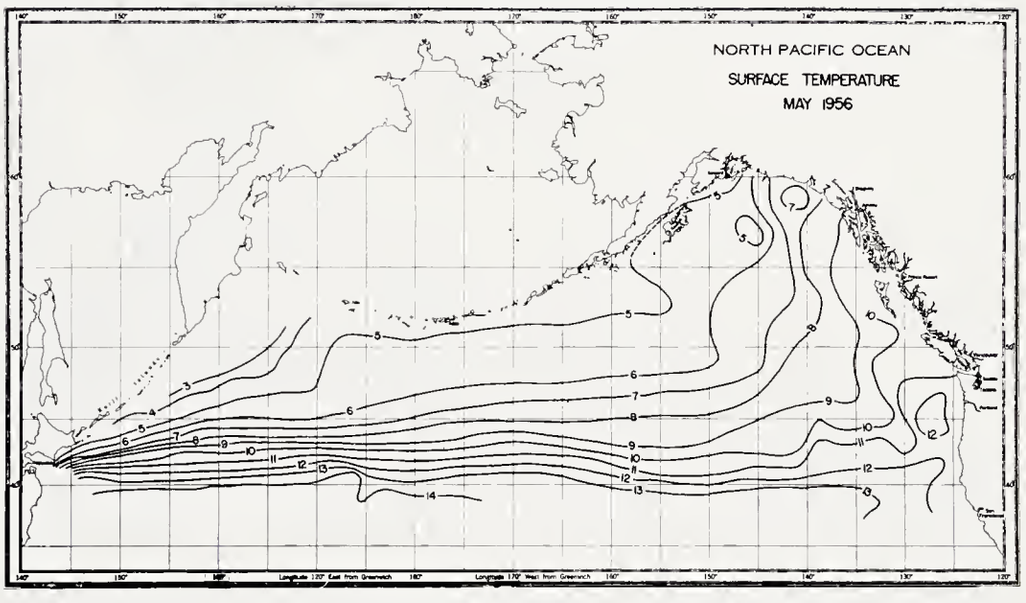


FIGURE 12a. Monthly mean sea surface temperature charts, January, February, March, 1956 (adapted from Saur and Eber, 1962).





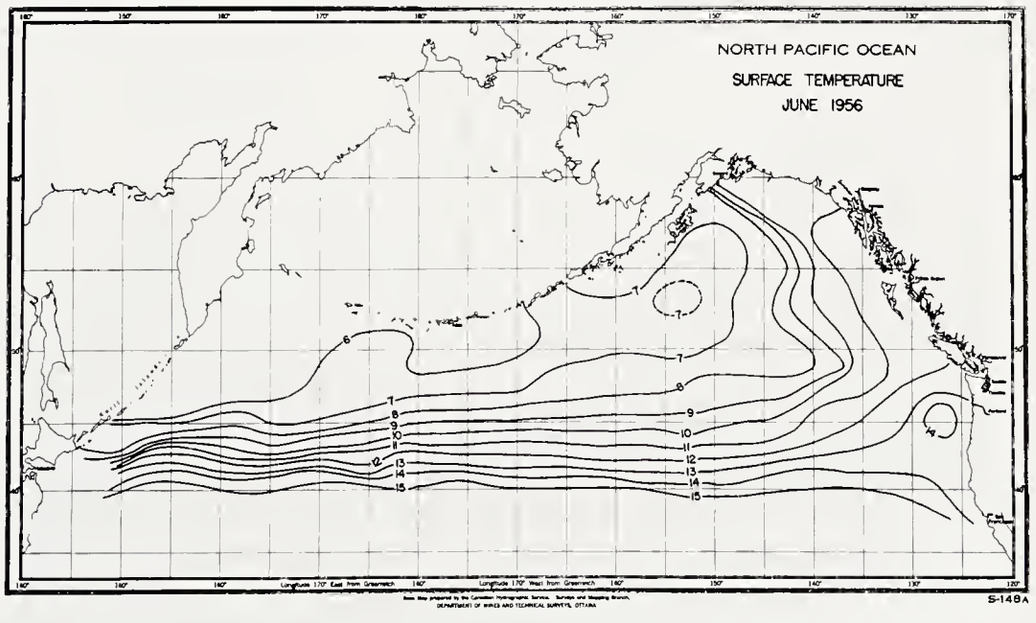


FIGURE 12b. Monthly mean sea surface temperature charts, April, May, June, 1956 (adapted from Saur and Eber, 1962).

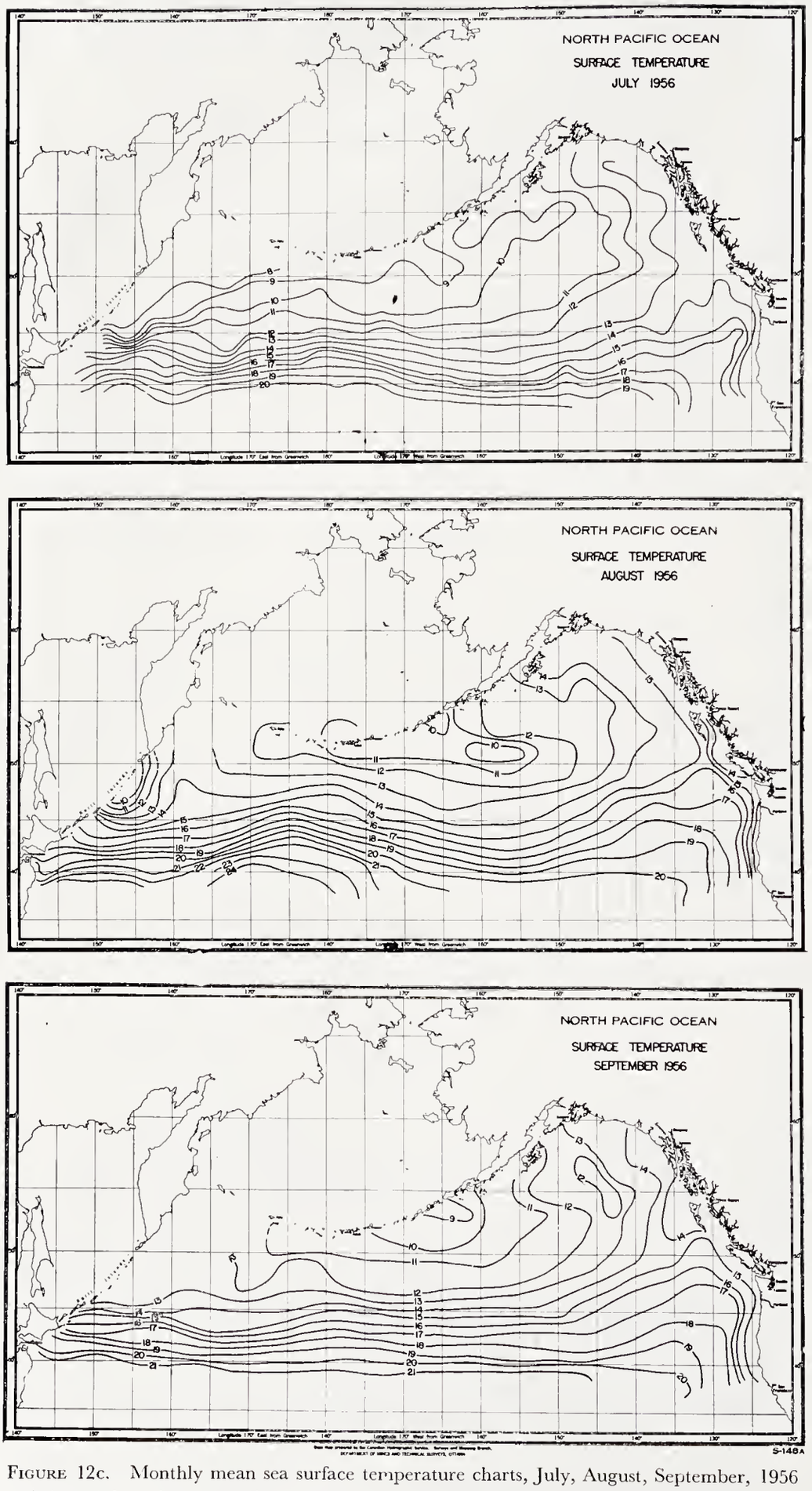


FIGURE 12c. Monthly mean sea surface temperature charts, July, August, September, 1956 (adapted from Saur and Eber, 1962).

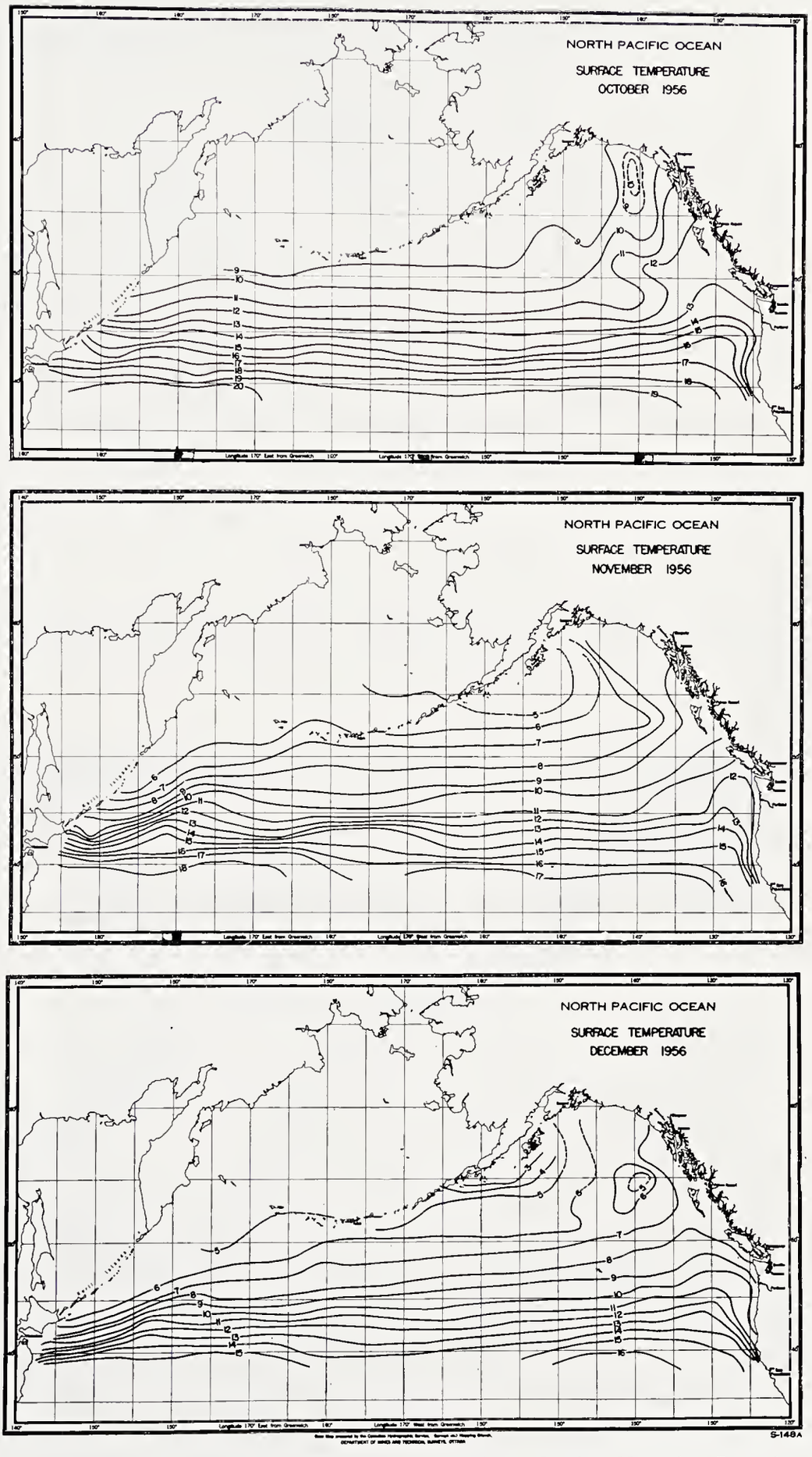


FIGURE 12d. Monthly mean sea surface temperature charts, October, November, December, 1956 (adapted from Saur and Eber, 1962).

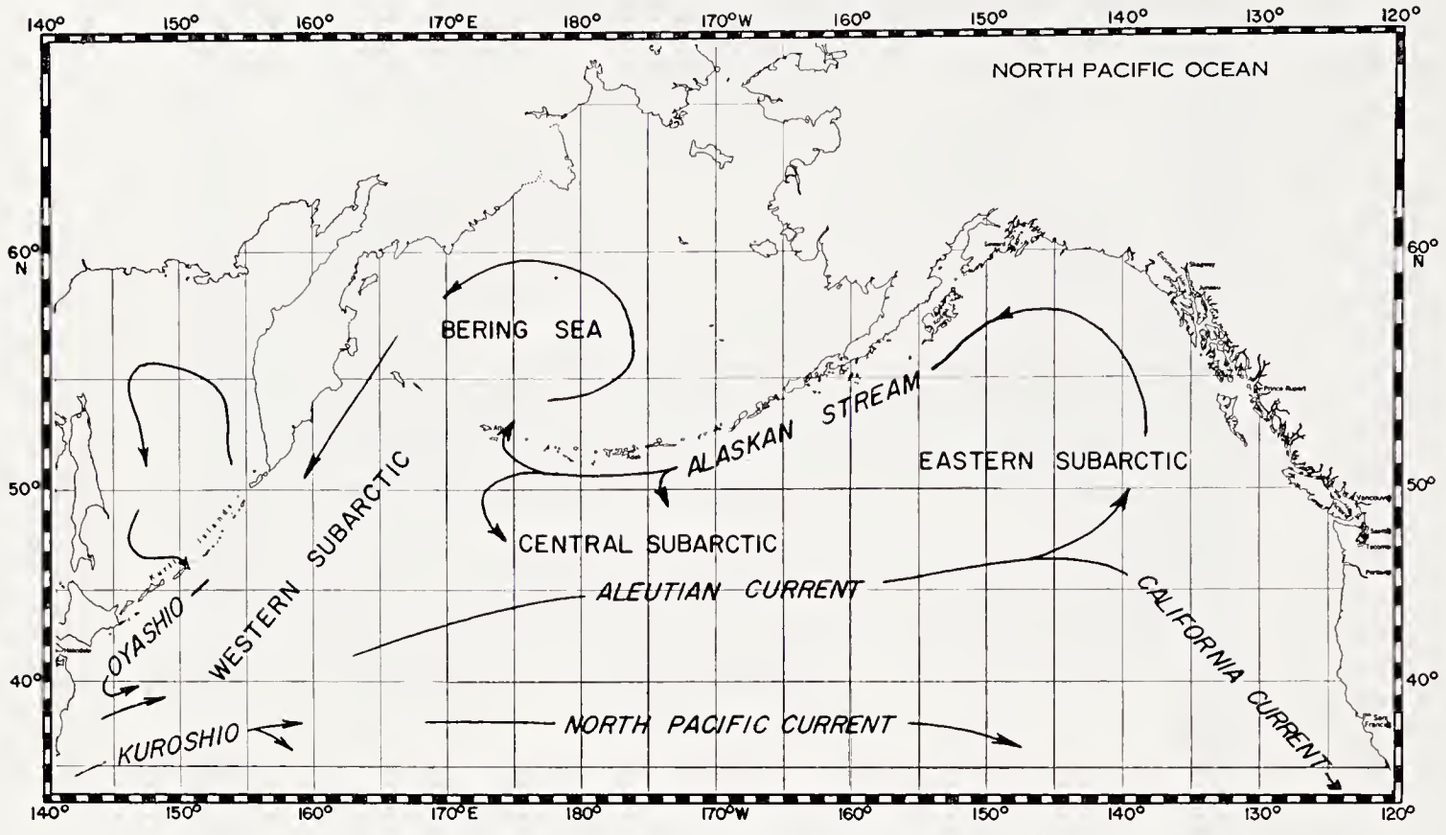


FIGURE 13. Recognized major current systems prior to 1955.

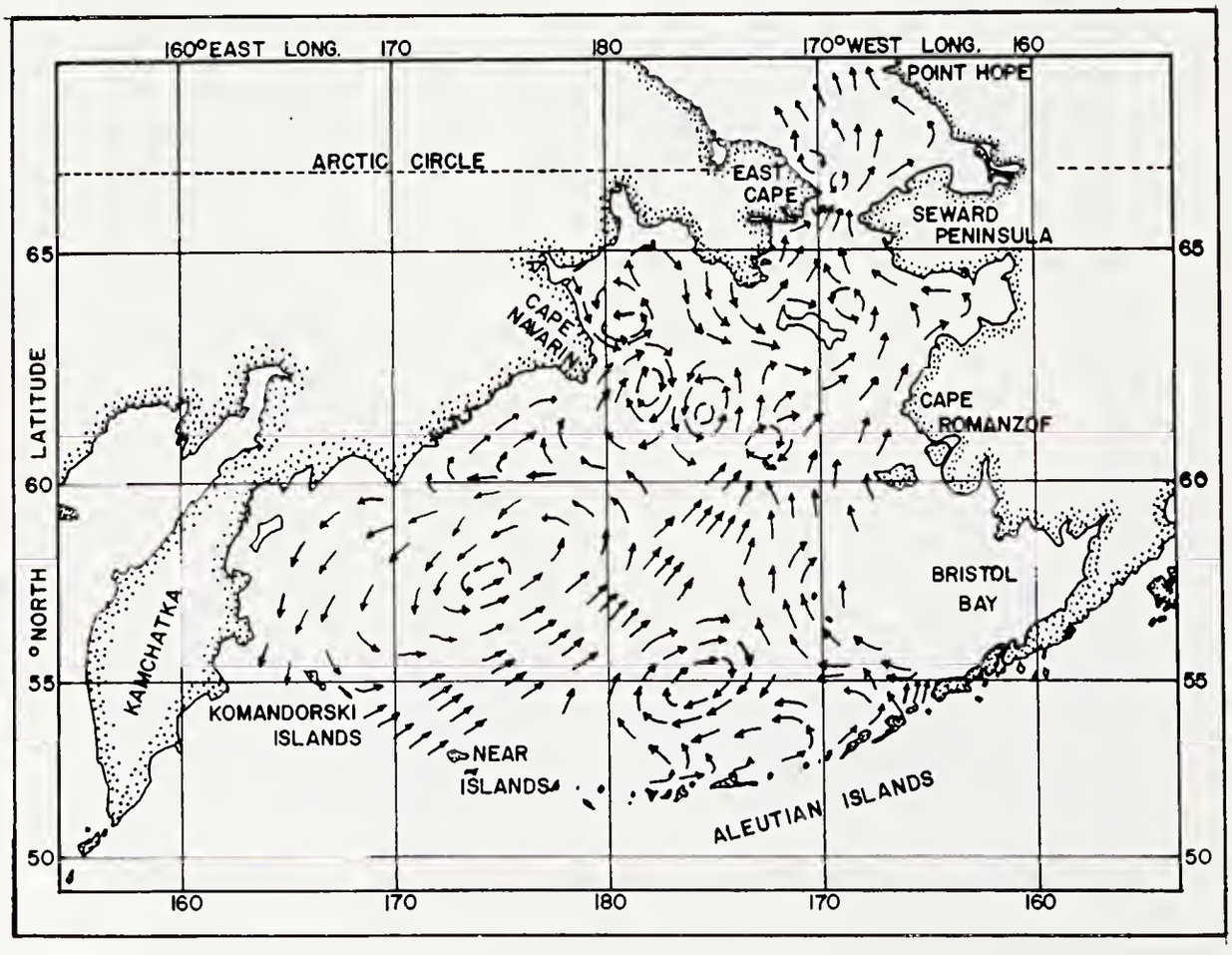


FIGURE 14. Surface circulation in the Bering Sea (Goodman *et al.*, 1942).

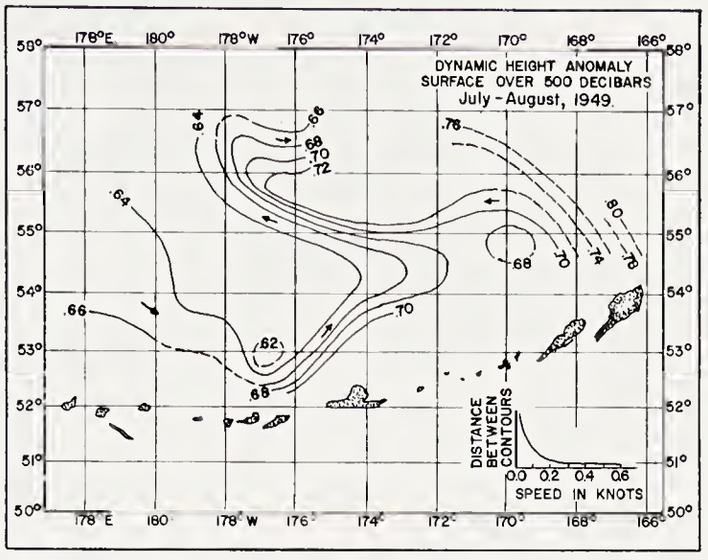


FIGURE 15. Dynamic height anomaly, surface over 500 decibars, Bering Sea, July-August 1949 (Saur *et al.*, 1952).

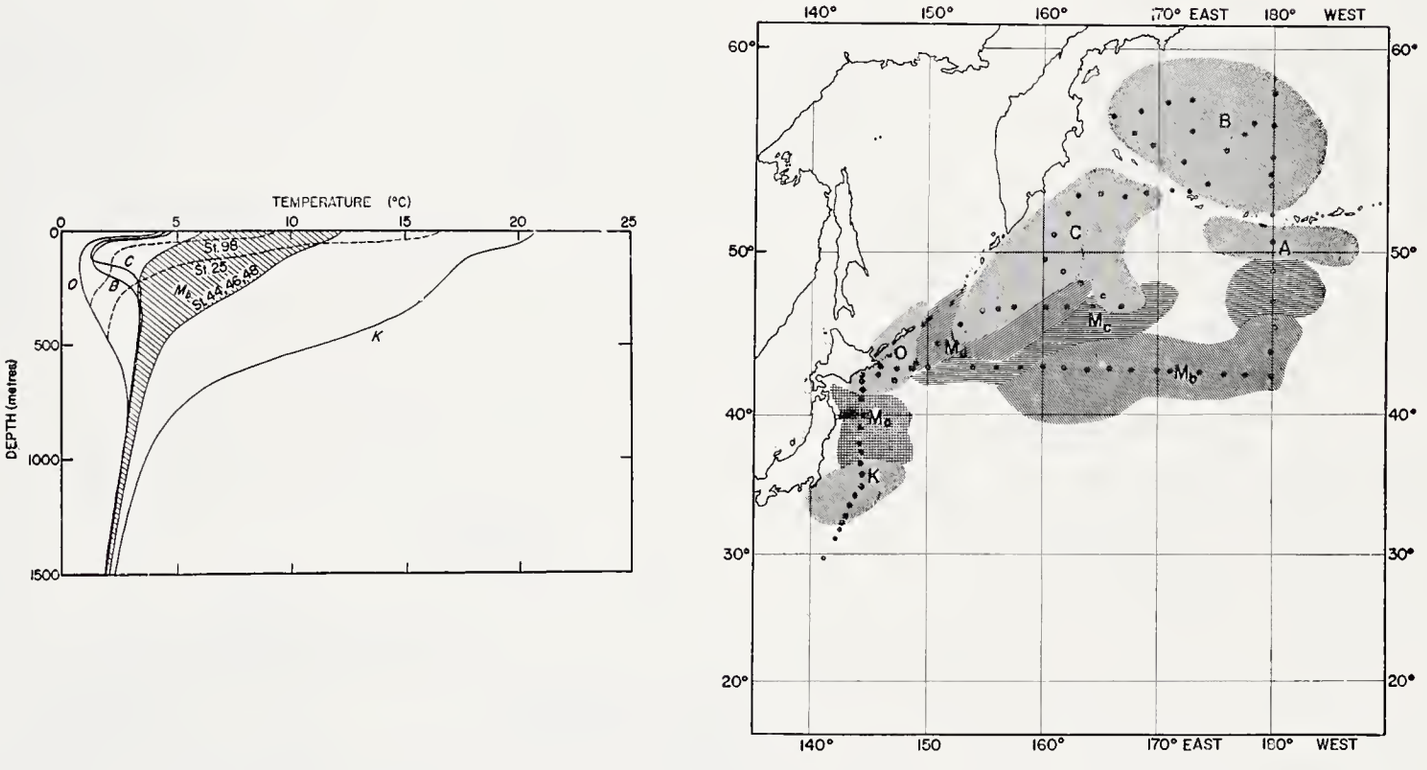


FIGURE 16. Vertical temperature curves of typical water systems and their regional distributions in the western Subarctic Region (Hirano, 1957a).

Left: Vertical temperature curves of typical water systems based on data from the R.V. *Tenyo Maru*, 1954 (Hirano, 1957a). K: Kuroshio water, O: Okhotsk water, B: Bering water, C: central water of the western Subarctic Region, M_b: Mixing water between the Kuroshio and the Okhotsk water. The right edge of M_b shows the curve at sts. 44, 46 and 48, approximately. Curves in broken line show the water in the mixing region M_a at sts. 25 and 98.

Right: Regional distributions of water systems in the western Subarctic Region based on data from the R.V. *Tenyo Maru*, 1954 (Hirano, 1957a). A: water originating from the Gulf of Alaska, M_a: water in the mixing region off the Sanriku, M_c: mixing water between the central water of the western Subarctic Region and the mixing water M_b, M_d: mixing water between the Okhotsk water and the central water of the western Subarctic Region.

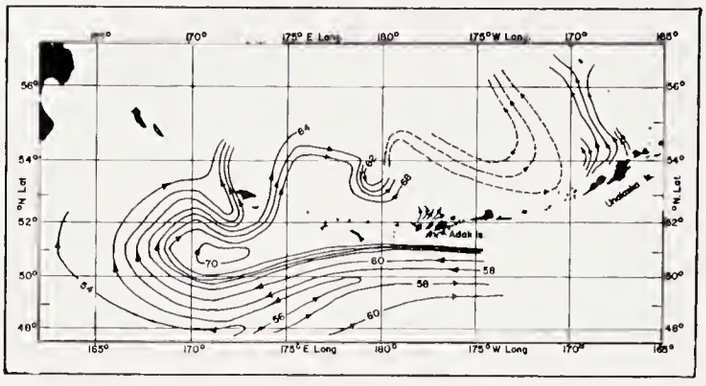


FIGURE 17. Geopotential topography, 100/750 decibars near the Aleutian Islands (Mishima and Nishizawa, 1955).

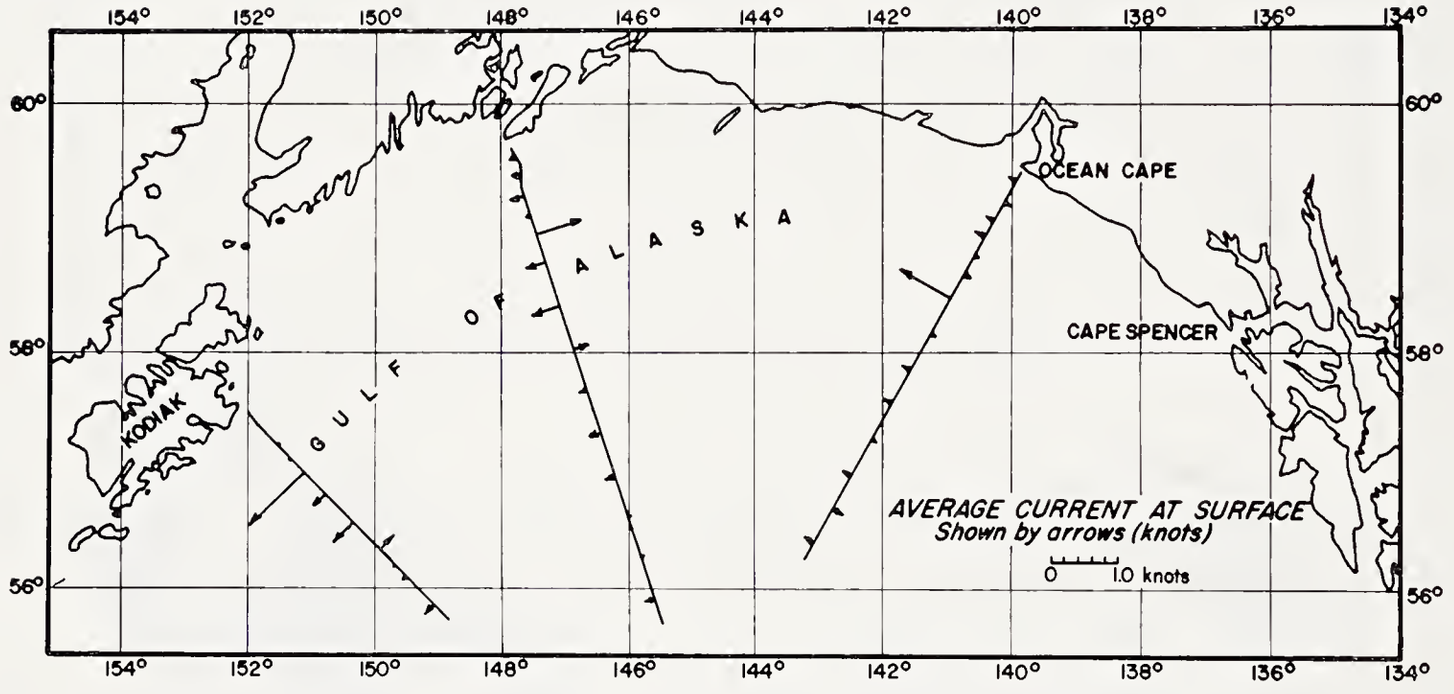


FIGURE 18. Calculated surface currents relative to bottom in Gulf of Alaska (Thompson *et al.*, 1936).

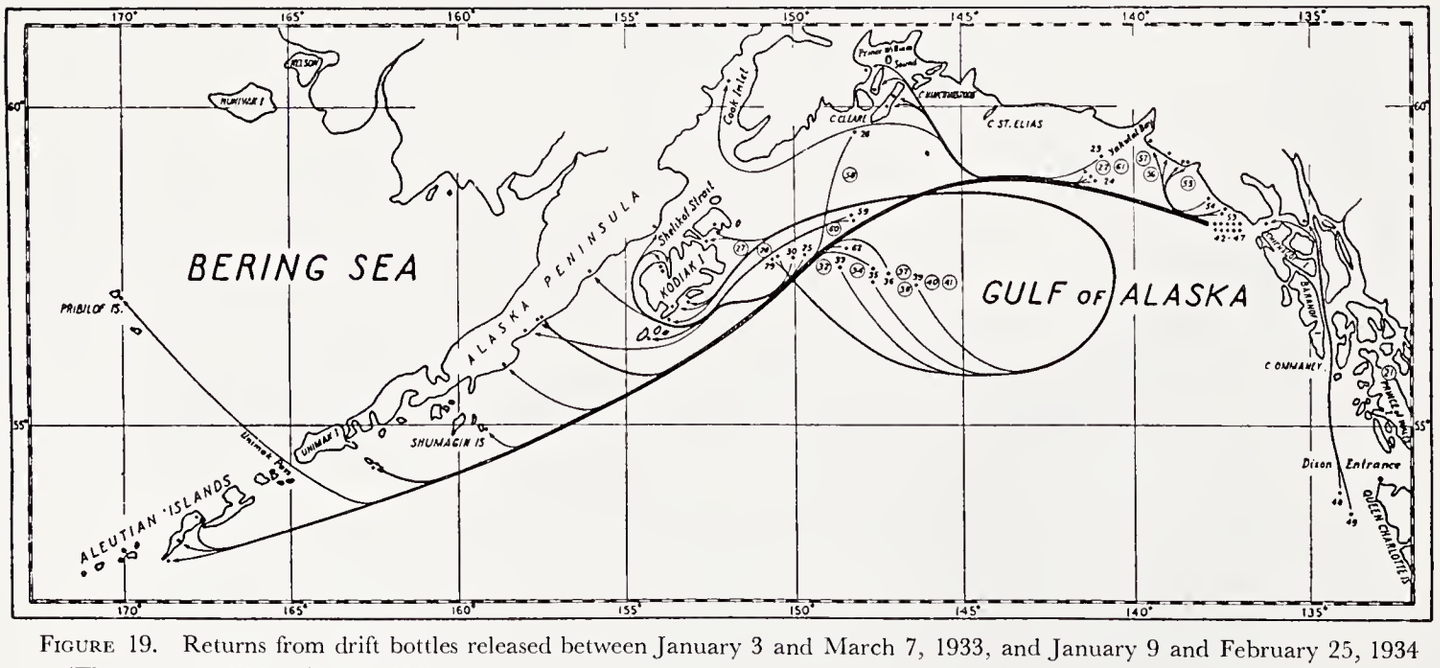


FIGURE 19. Returns from drift bottles released between January 3 and March 7, 1933, and January 9 and February 25, 1934 (Thomposn and Van Cleve, 1936).

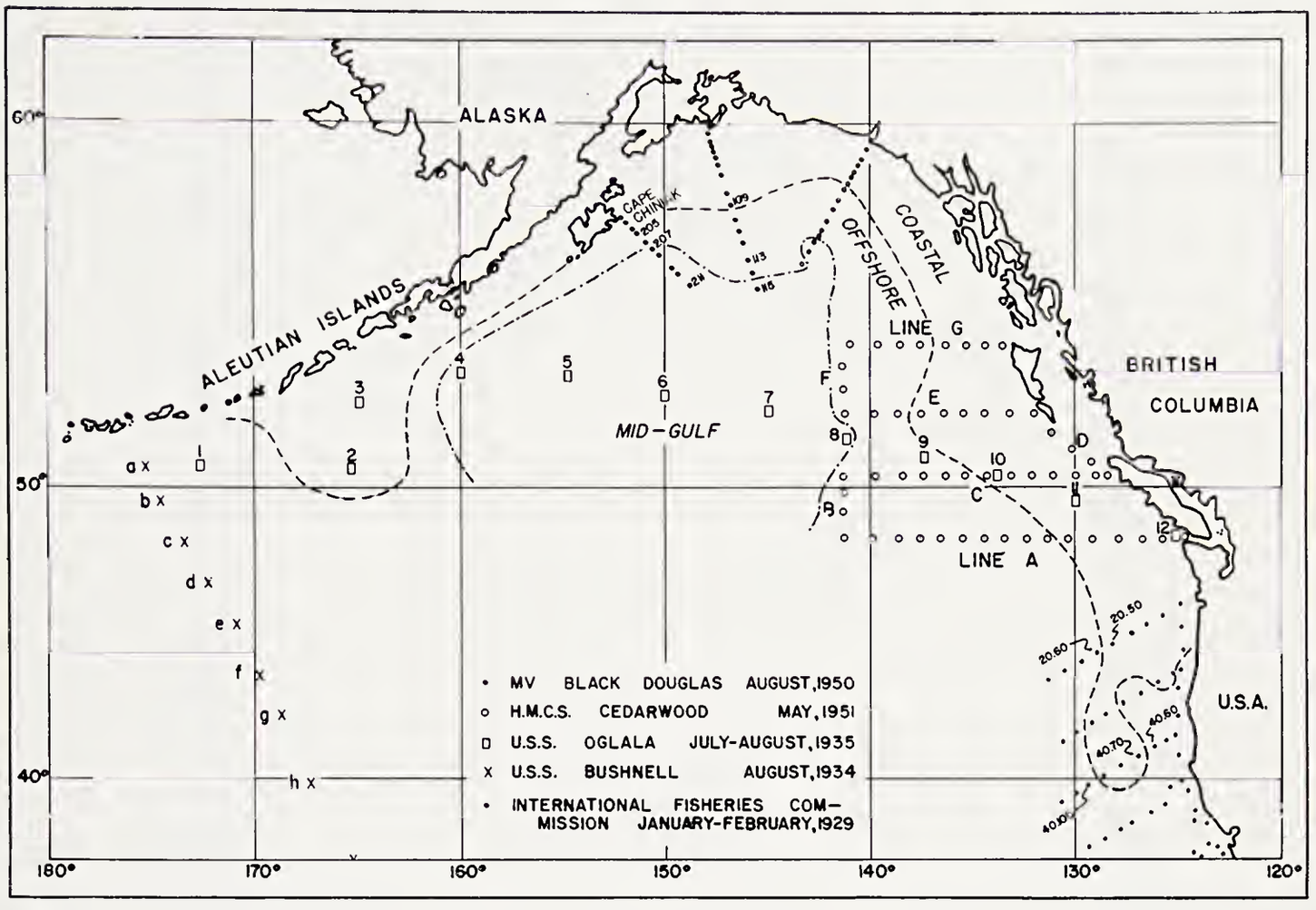


FIGURE 20. Water masses in the Gulf of Alaska (Doe, 1955).

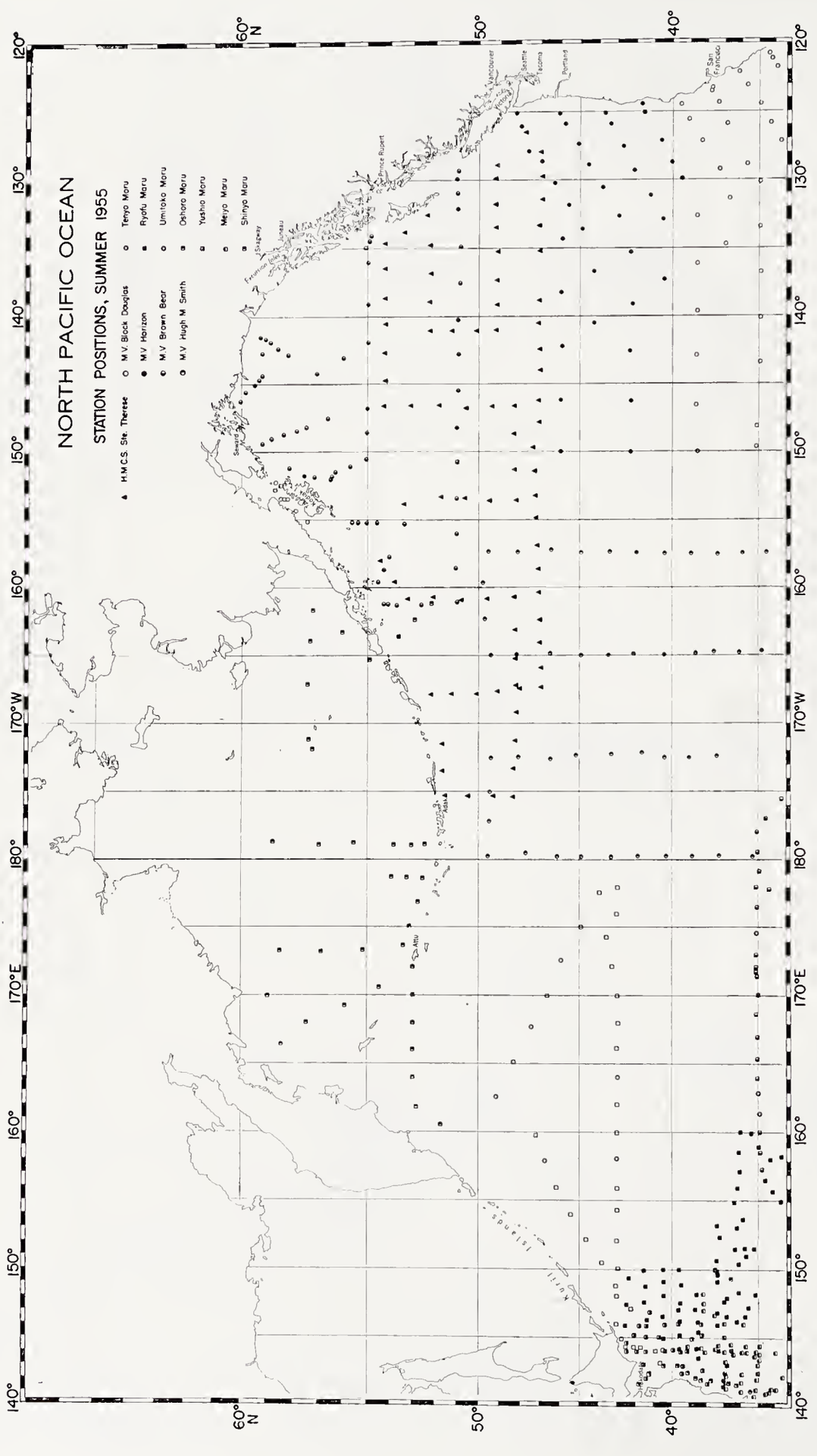


FIGURE 21. Station positions, summer 1955.

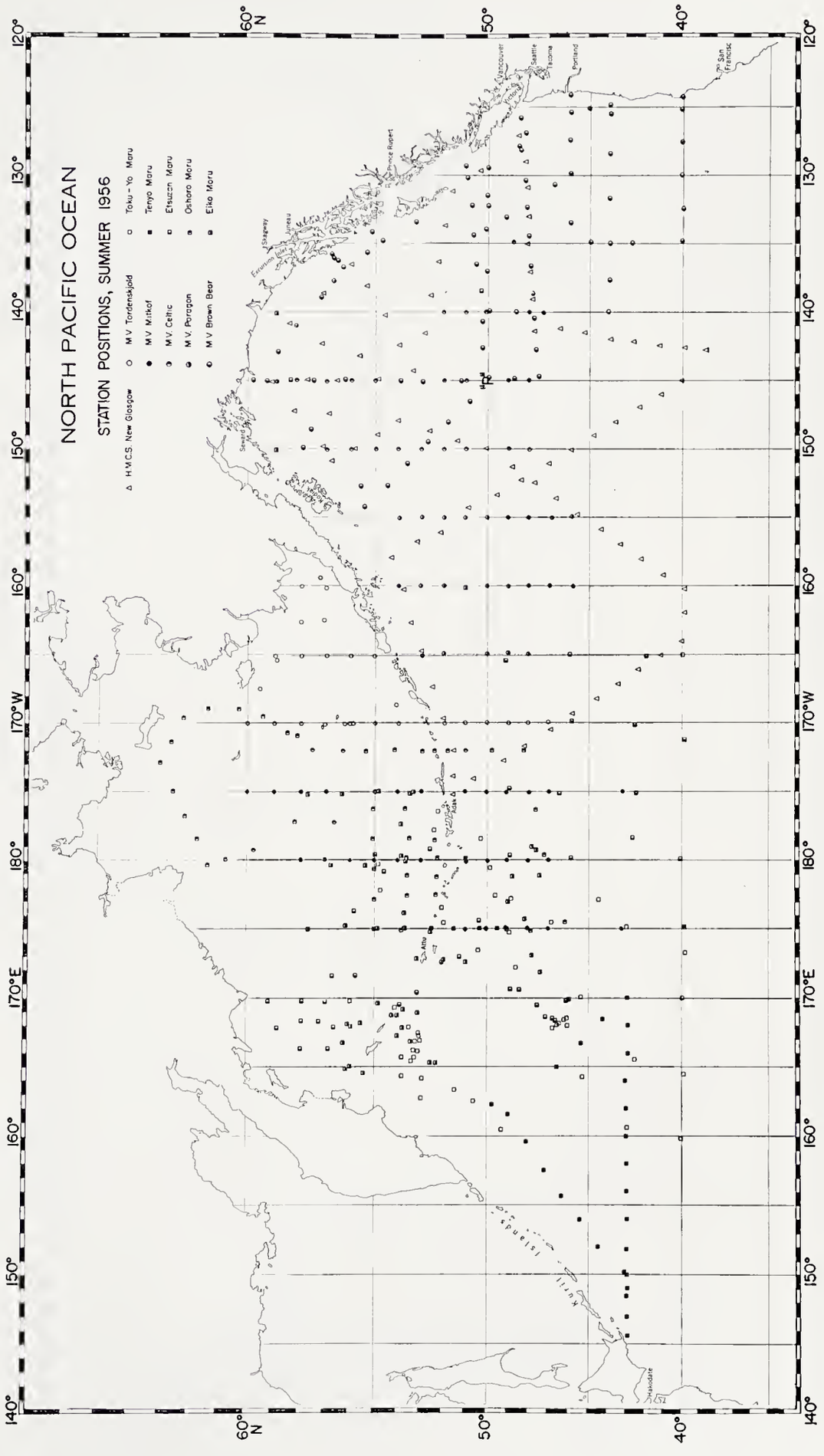


FIGURE 22. Station positions, summer 1956.

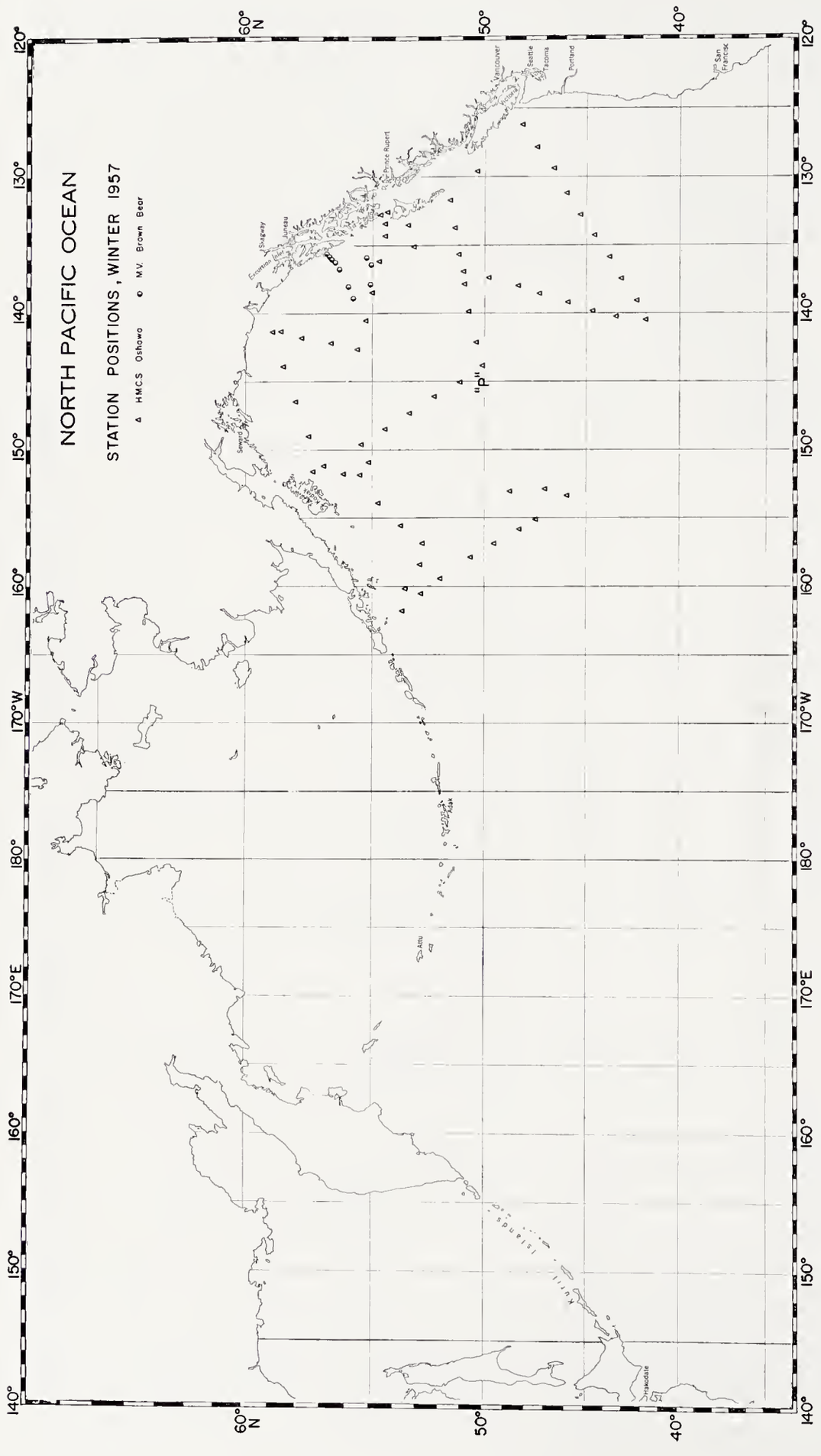


FIGURE 23. Station positions, winter 1957.

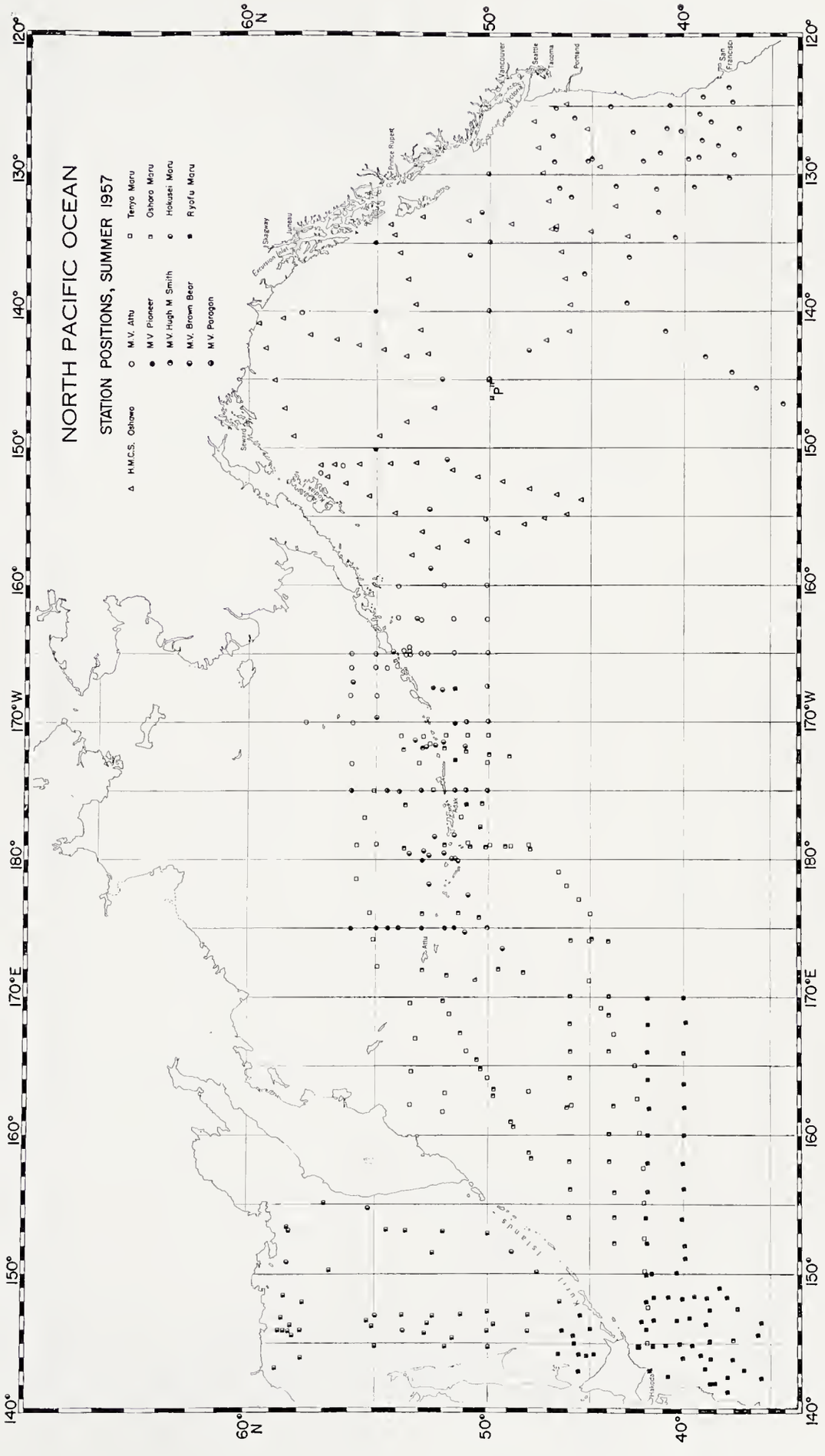


FIGURE 24. Station positions, summer 1957.

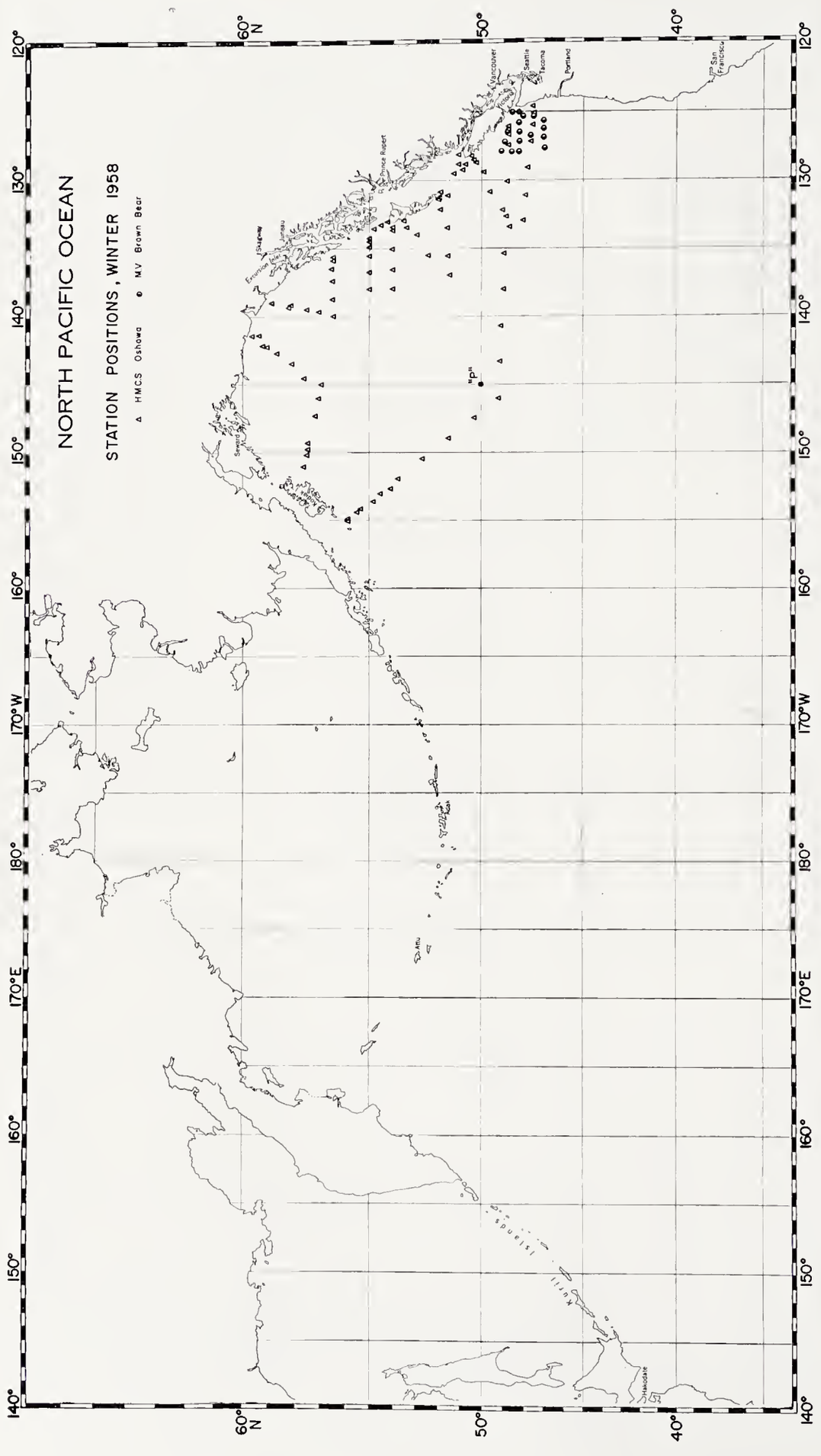


FIGURE 25. Station positions, winter 1958.

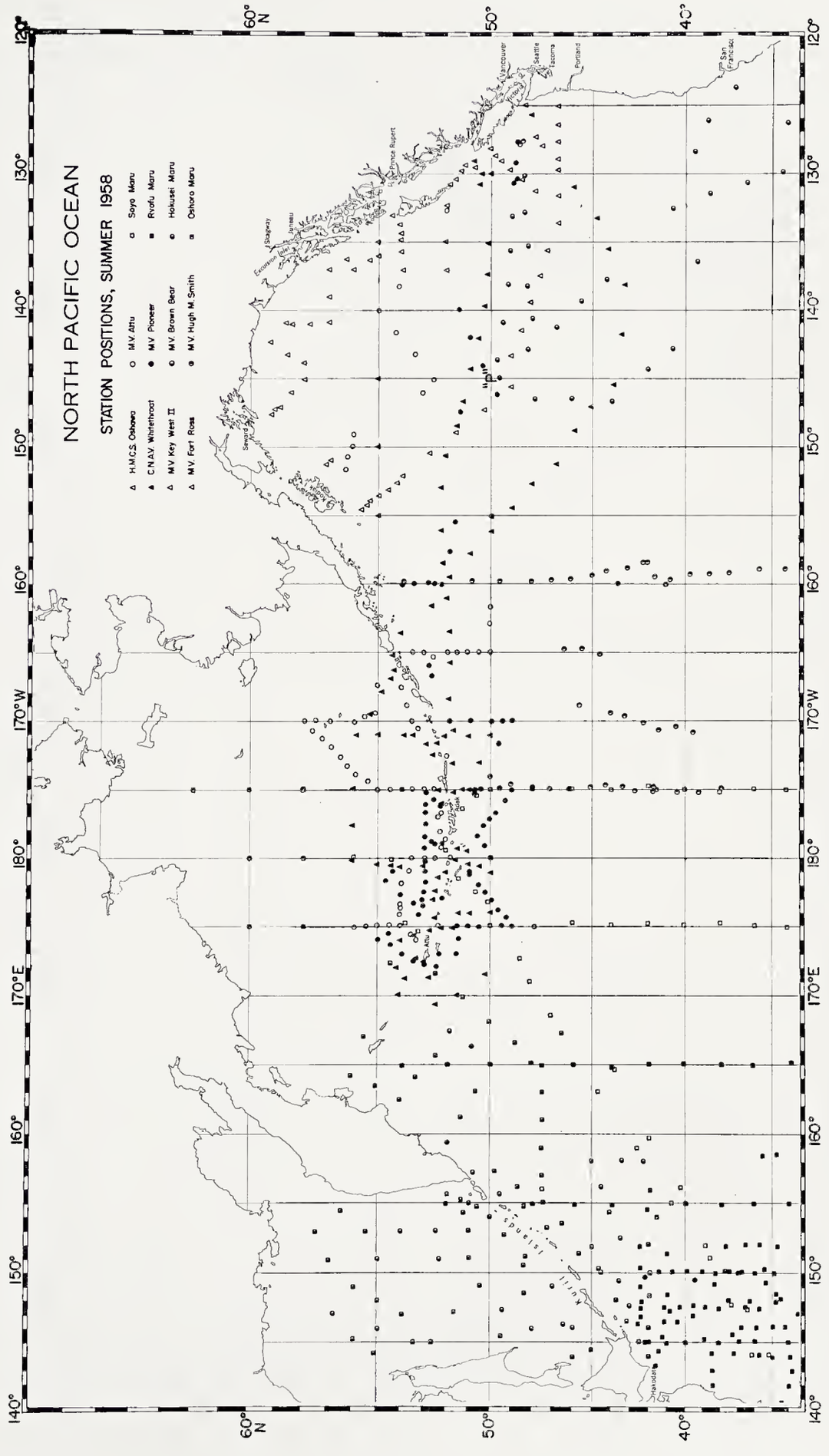


FIGURE 26. Station positions, summer 1958.

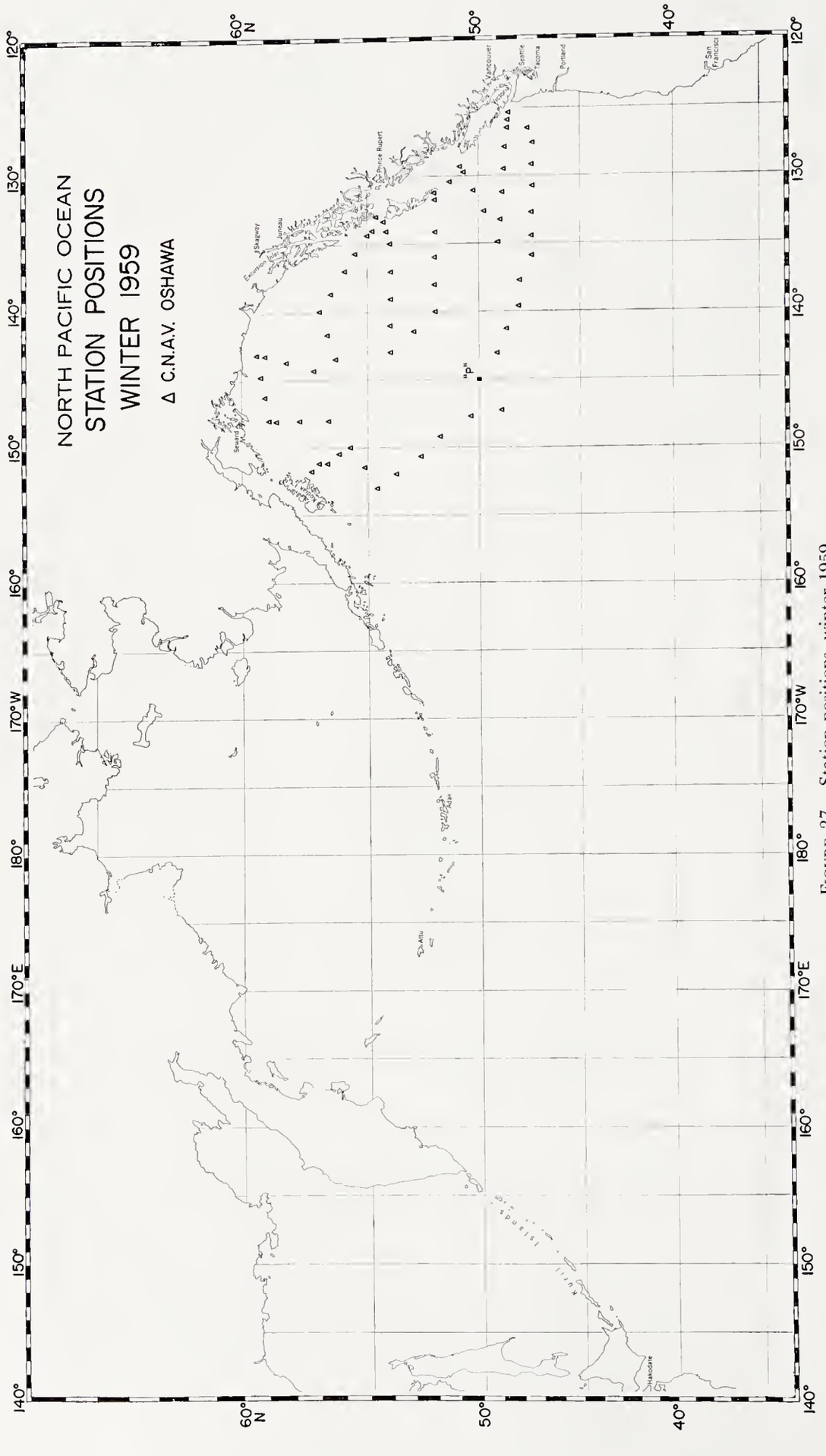


FIGURE 27. Station positions, winter 1959.

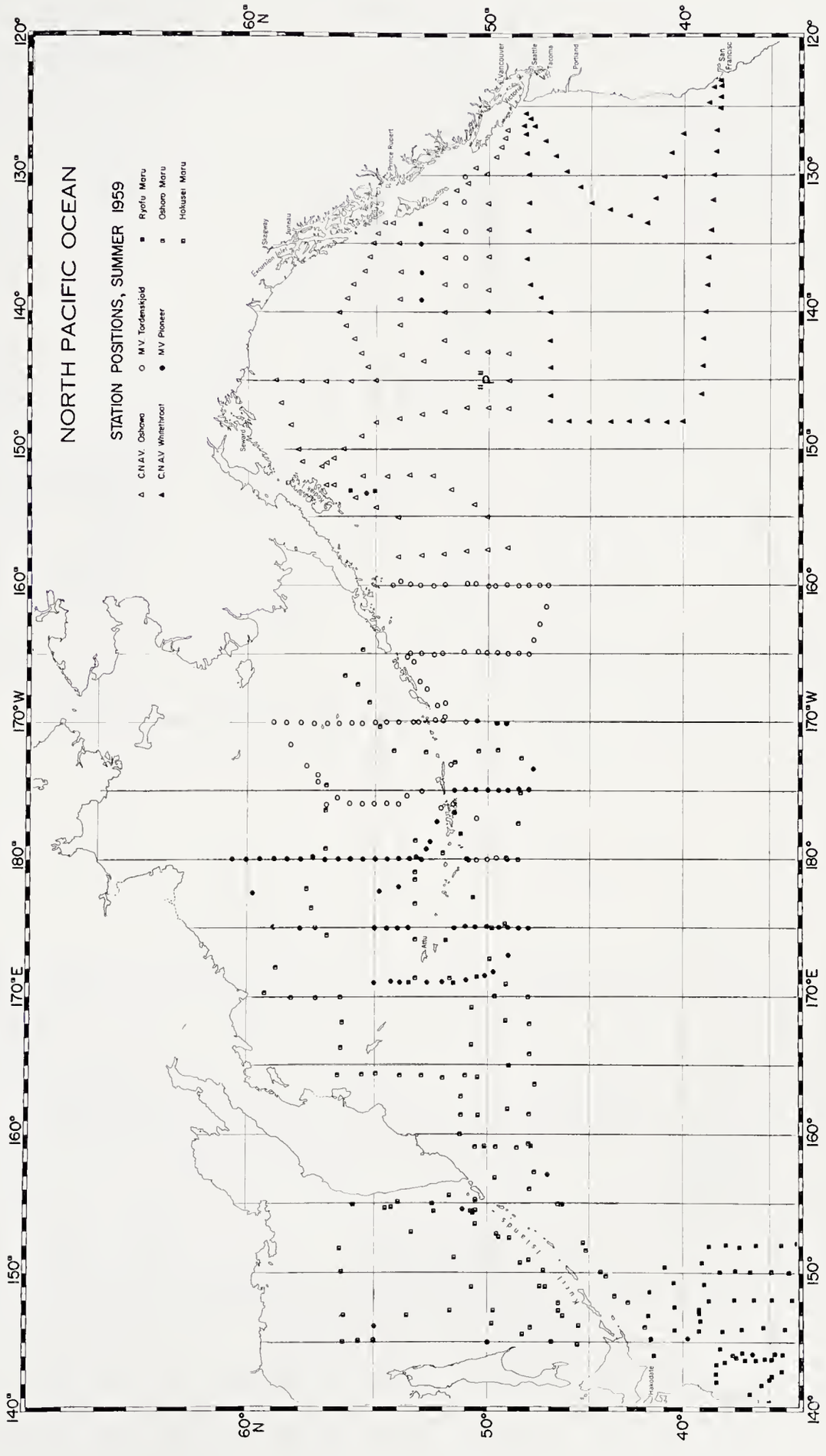


FIGURE 28. Station positions, summer 1959.

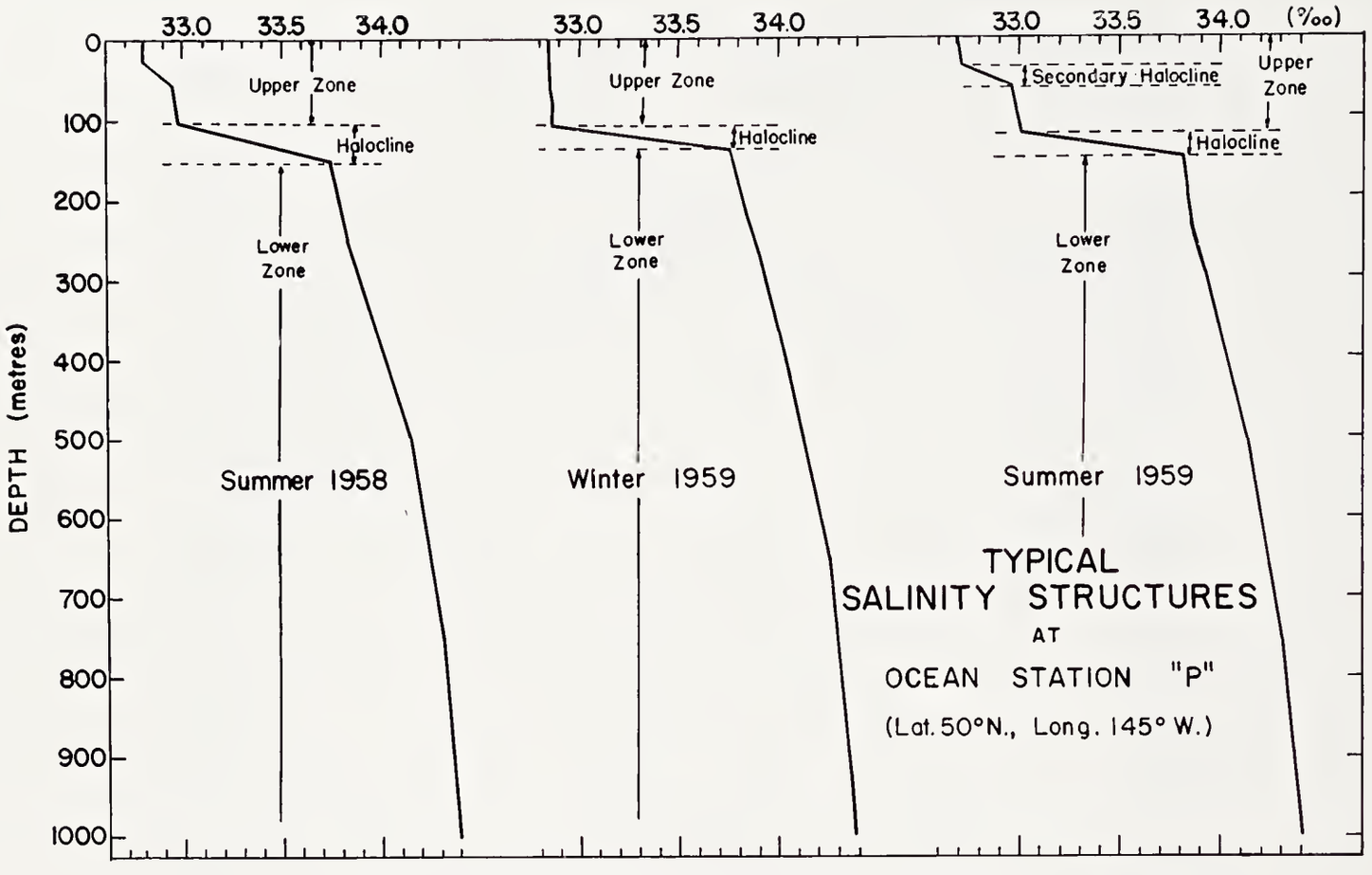


FIGURE 29. Typical salinity structures at Ocean Station "P".

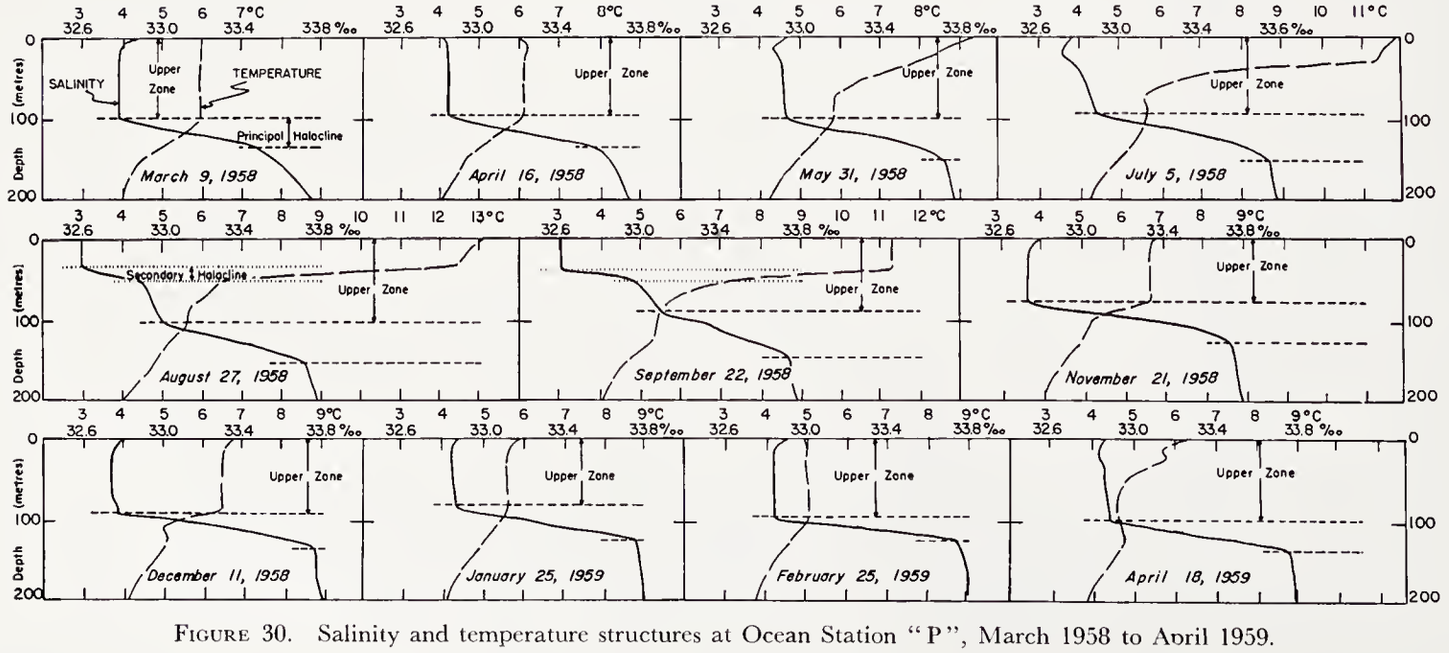


FIGURE 30. Salinity and temperature structures at Ocean Station "P", March 1958 to April 1959.

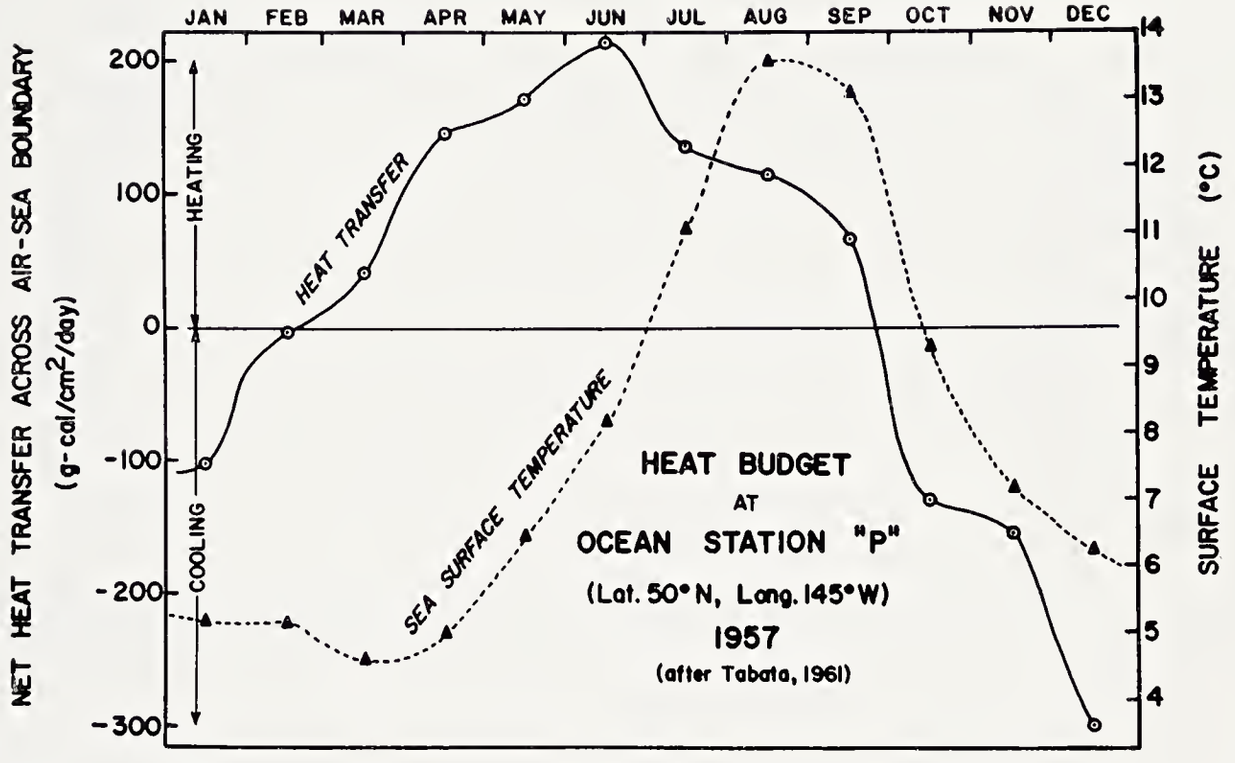


FIGURE 31. Heat budget at Ocean Station "P", 1957 (after Tabata, 1961).

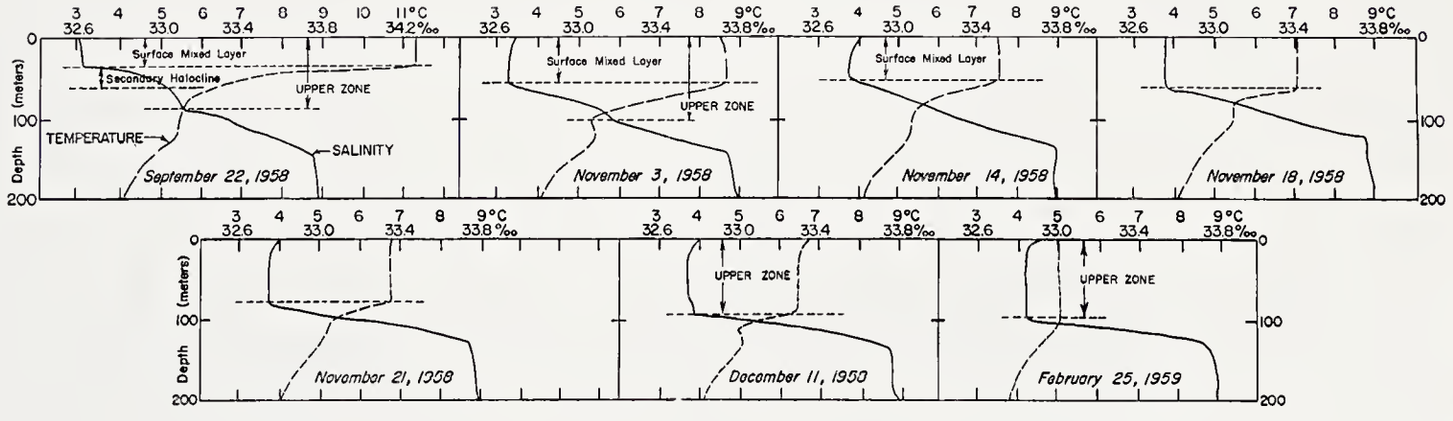


FIGURE 32. Salinity and temperature structures at Ocean Station "P", September 1958 to February 1959.

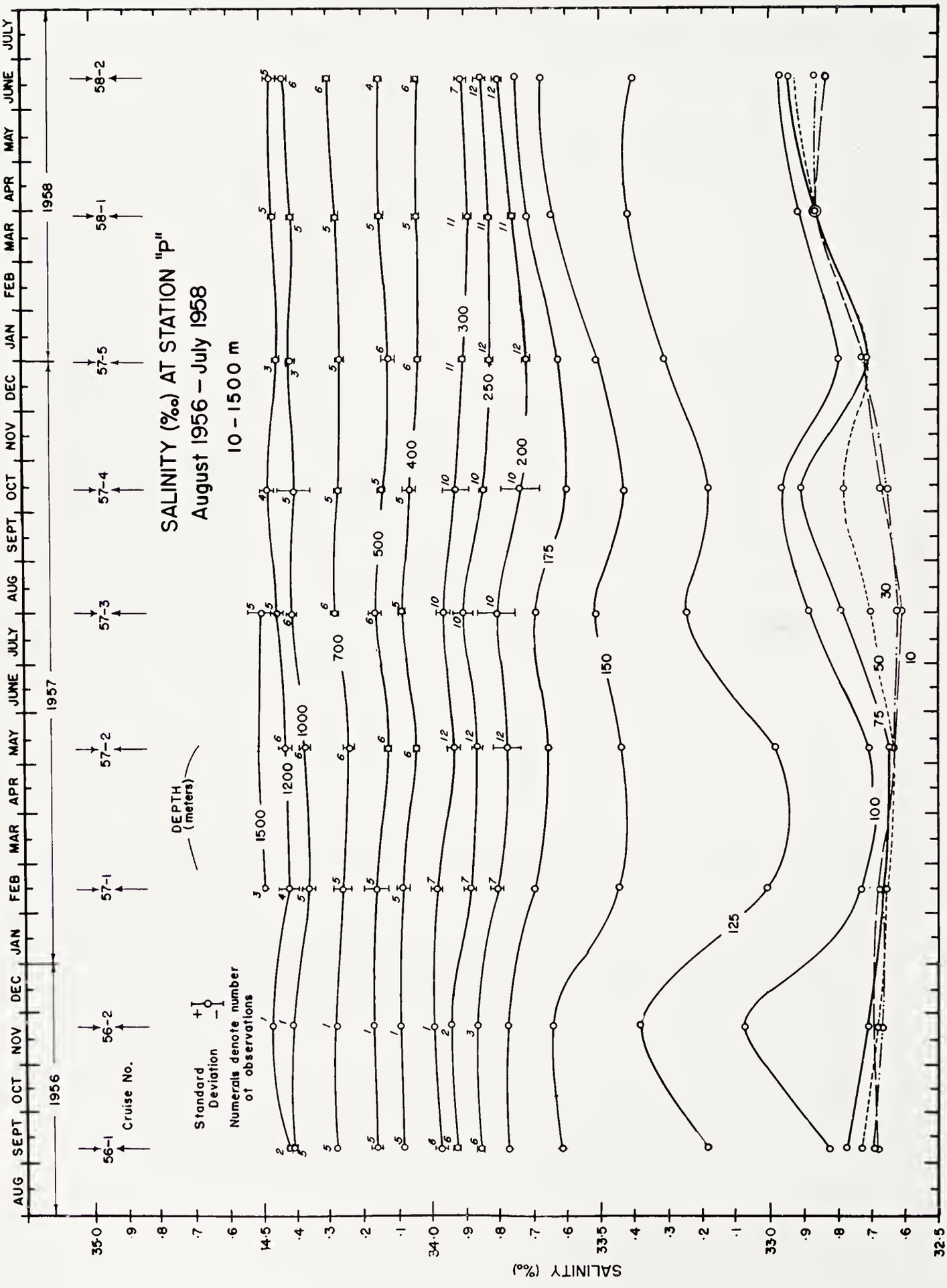


FIGURE 33. Values of salinity at selected depths at Ocean Station "P", August 1956 to July 1958 (Tabata, 1961) (std. dev. not shown at 10 to 175 m.).

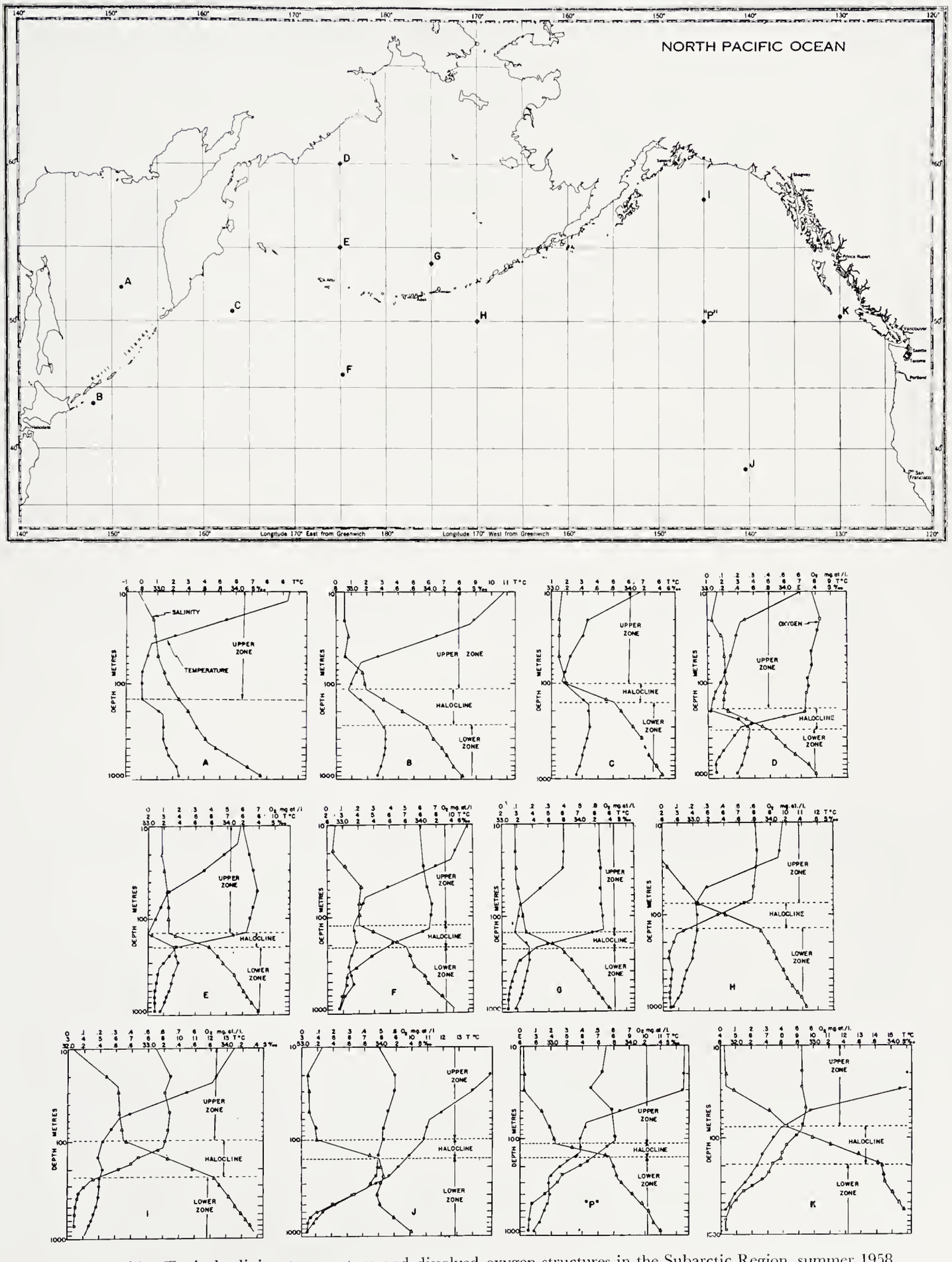
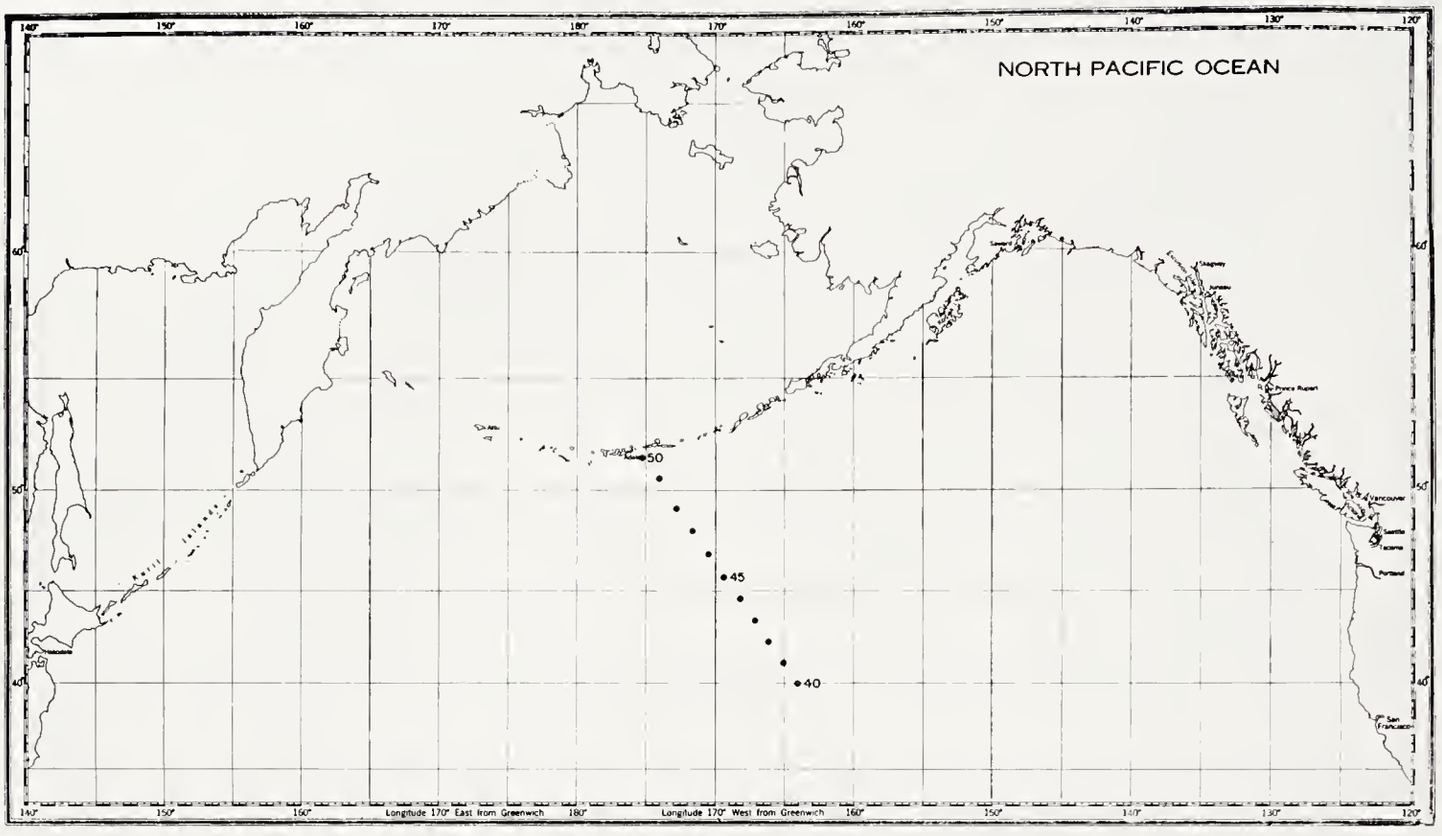


FIGURE 34. Typical salinity, temperature and dissolved oxygen structures in the Subarctic Region, summer 1958.



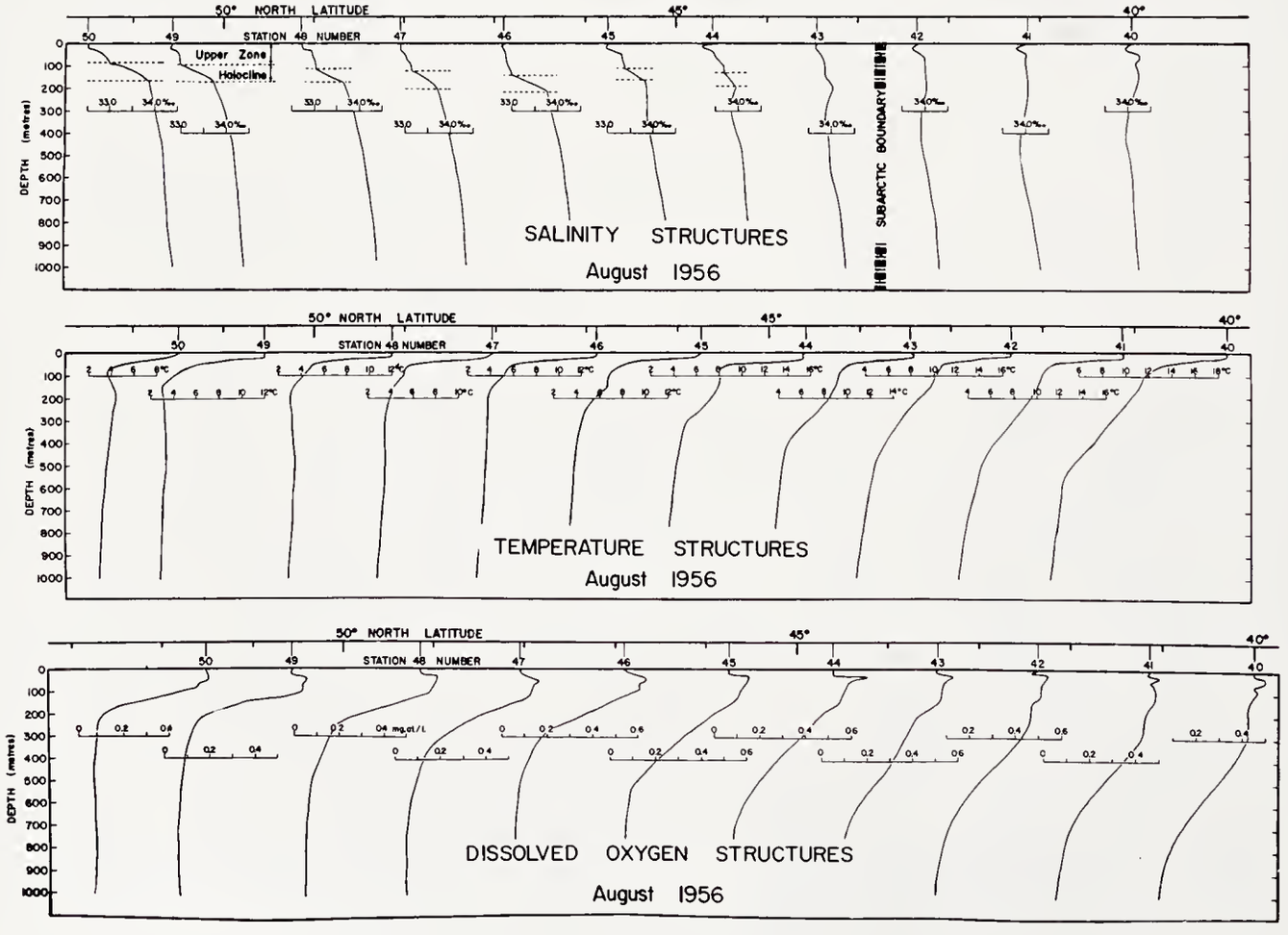


FIGURE 35. Sequence of salinity, temperature, and dissolved oxygen structures from lat. 50°N. to 40°N., summer 1956.

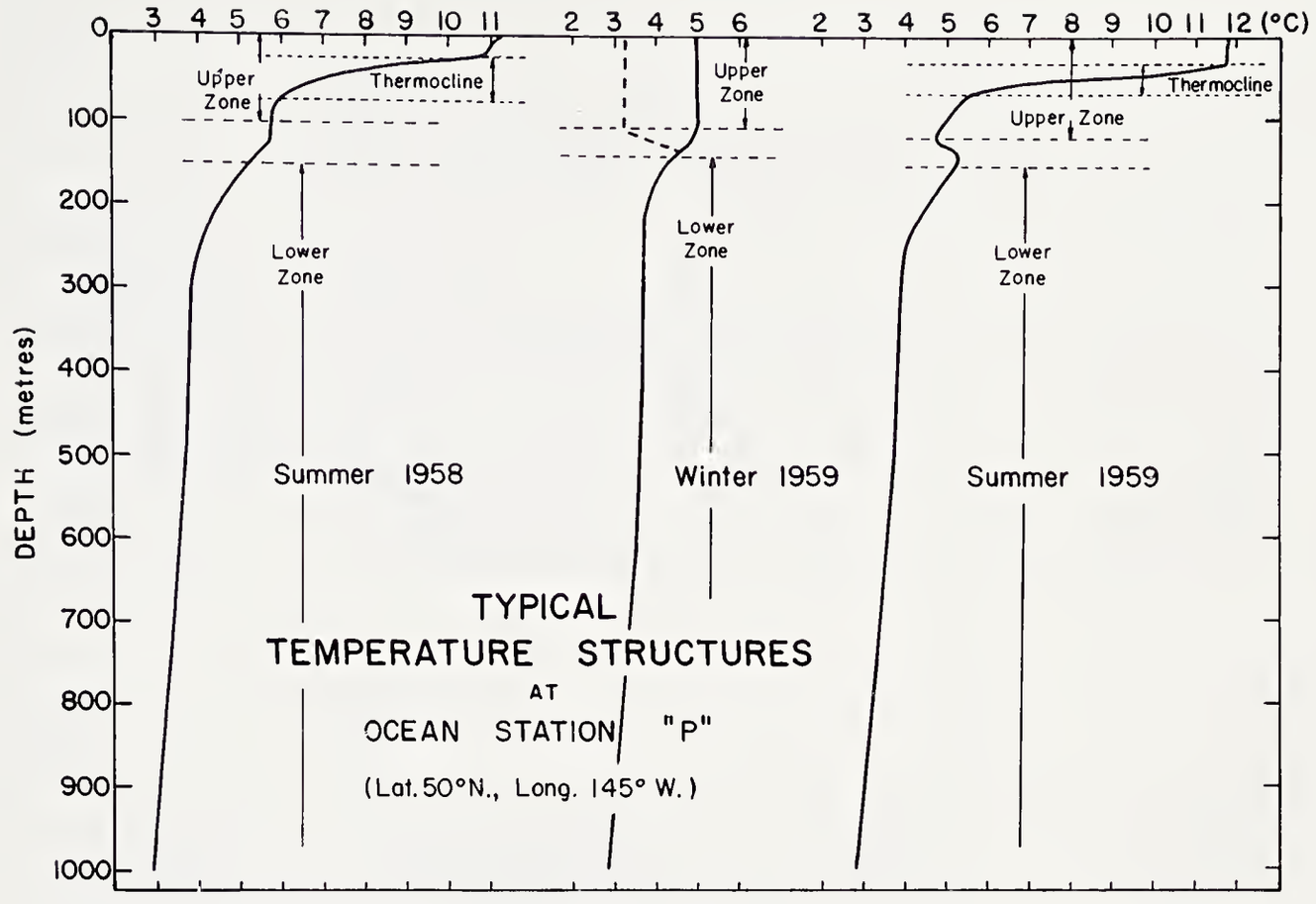


FIGURE 36. Typical temperature structures at Ocean Station "P" (dotted line at top winter structure indicates possible deviation with extreme cooling).

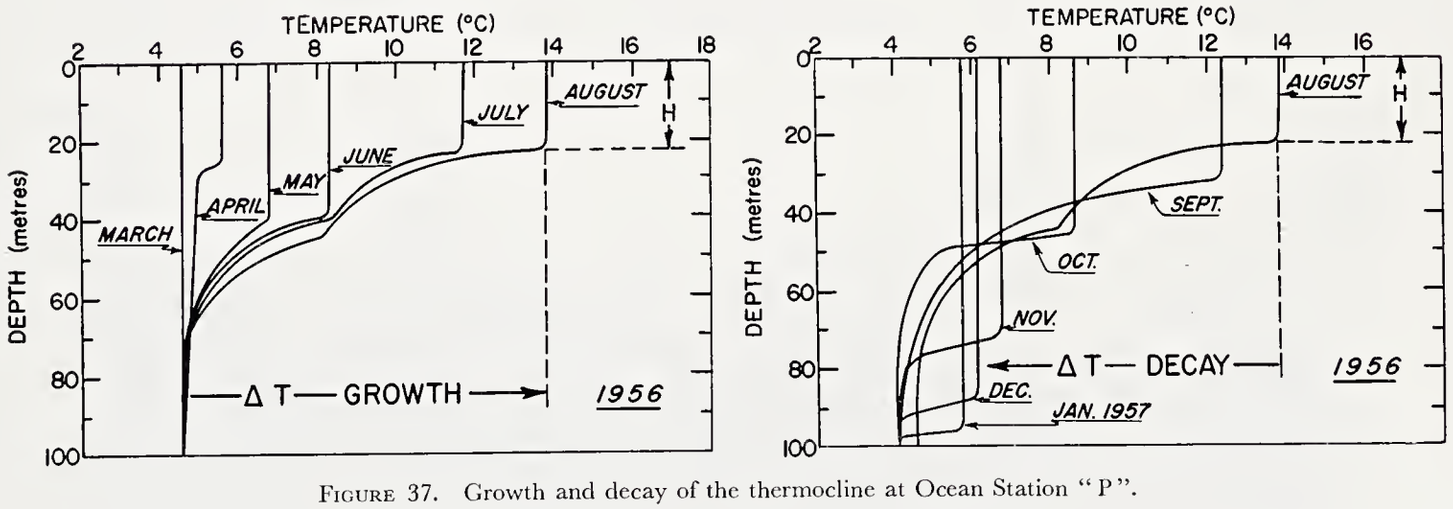


FIGURE 37. Growth and decay of the thermocline at Ocean Station "P".

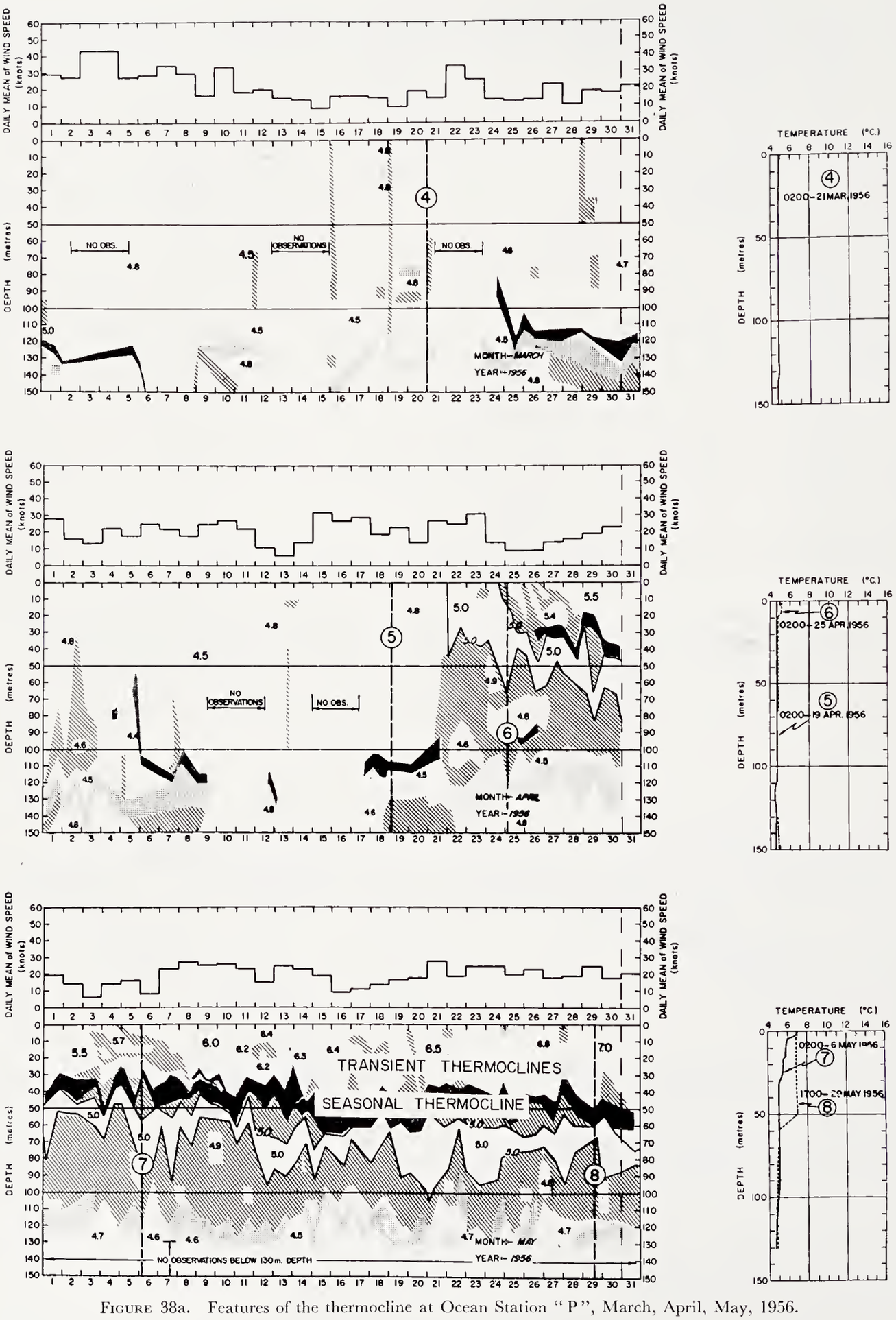


FIGURE 38a. Features of the thermocline at Ocean Station "P", March, April, May, 1956.

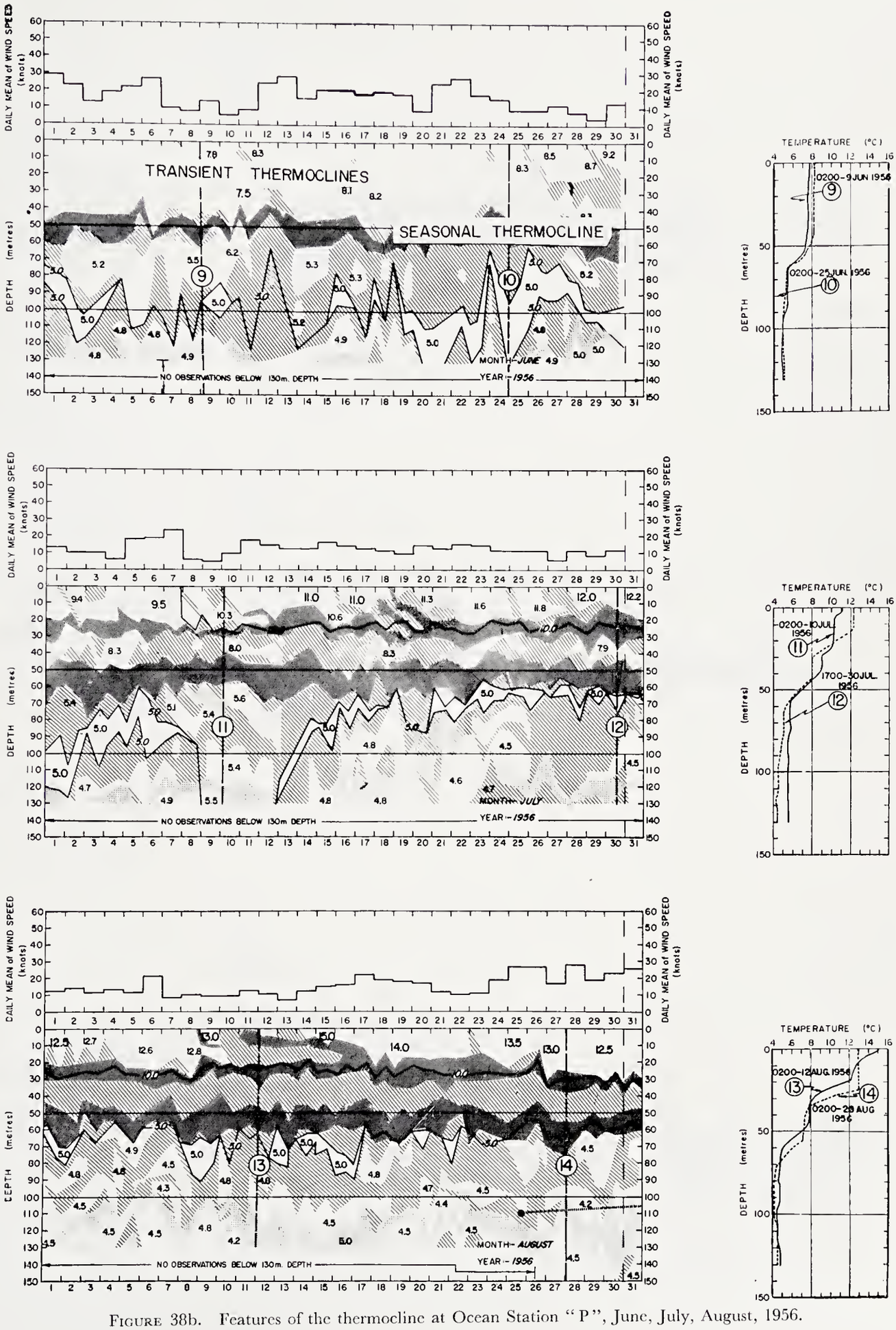


FIGURE 38b. Features of the thermocline at Ocean Station "P", June, July, August, 1956.

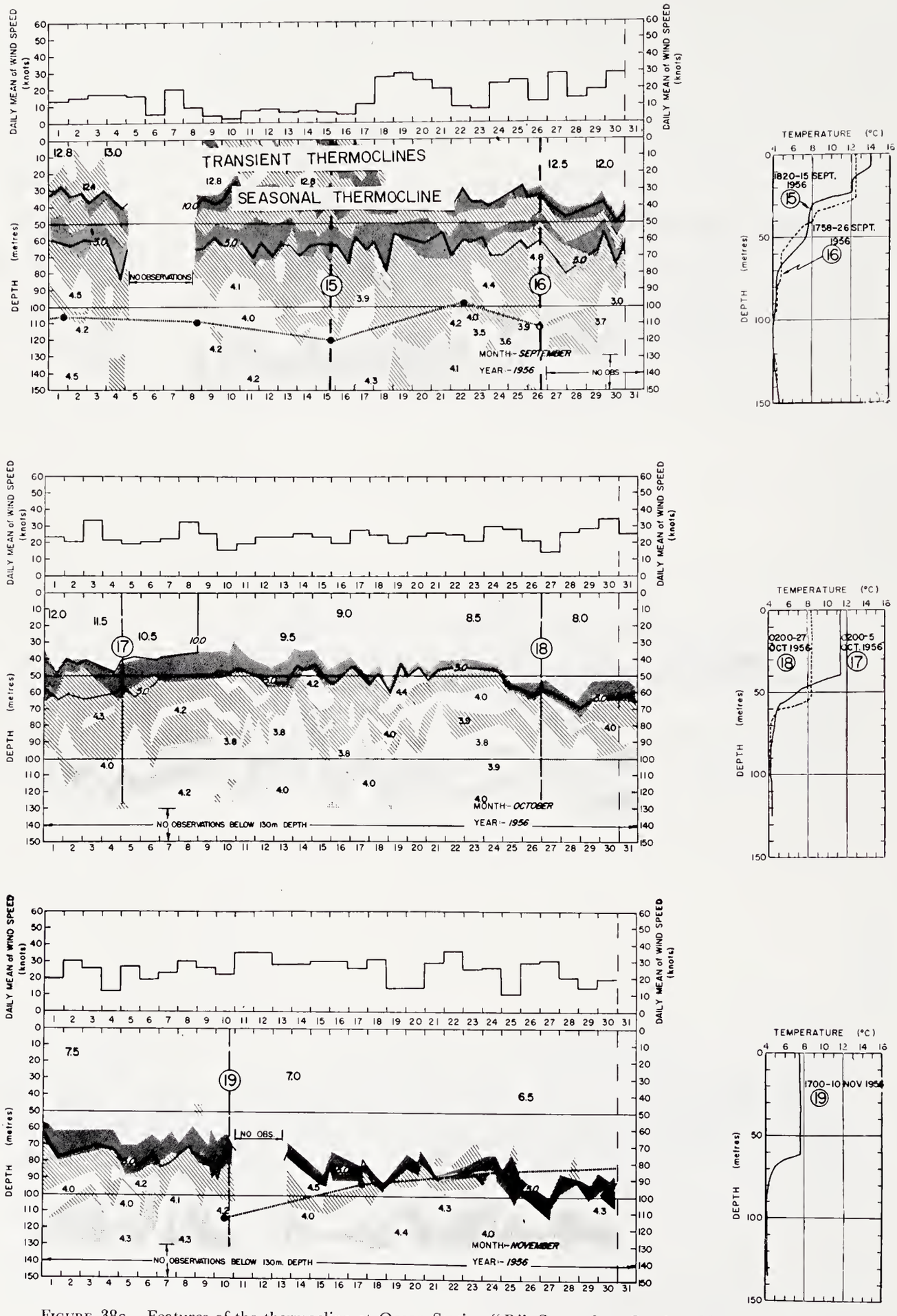


FIGURE 38c. Features of the thermocline at Ocean Station "P", September, October, November, 1956.

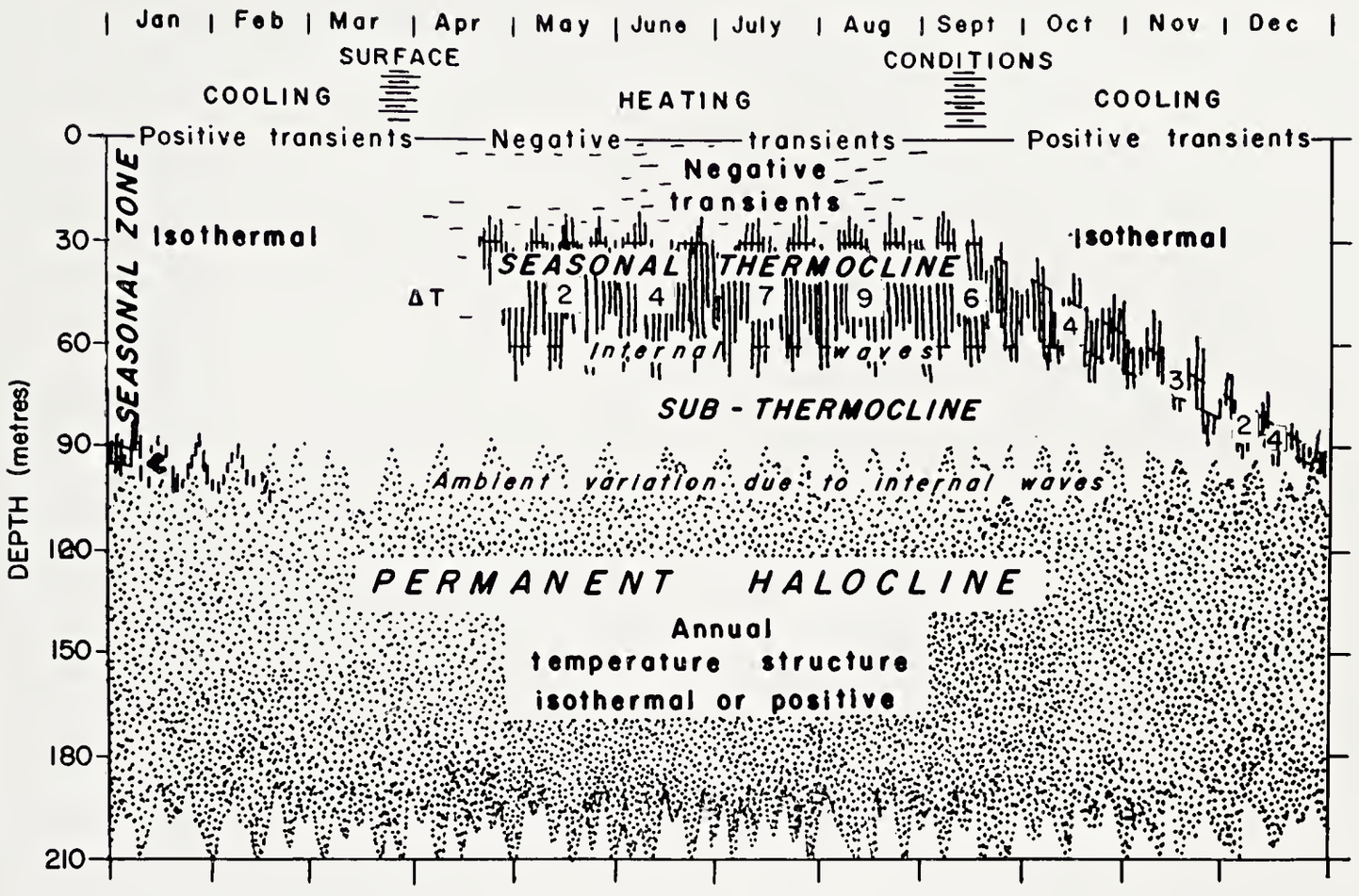


FIGURE 39. Schematic diagram of significant features of structure.

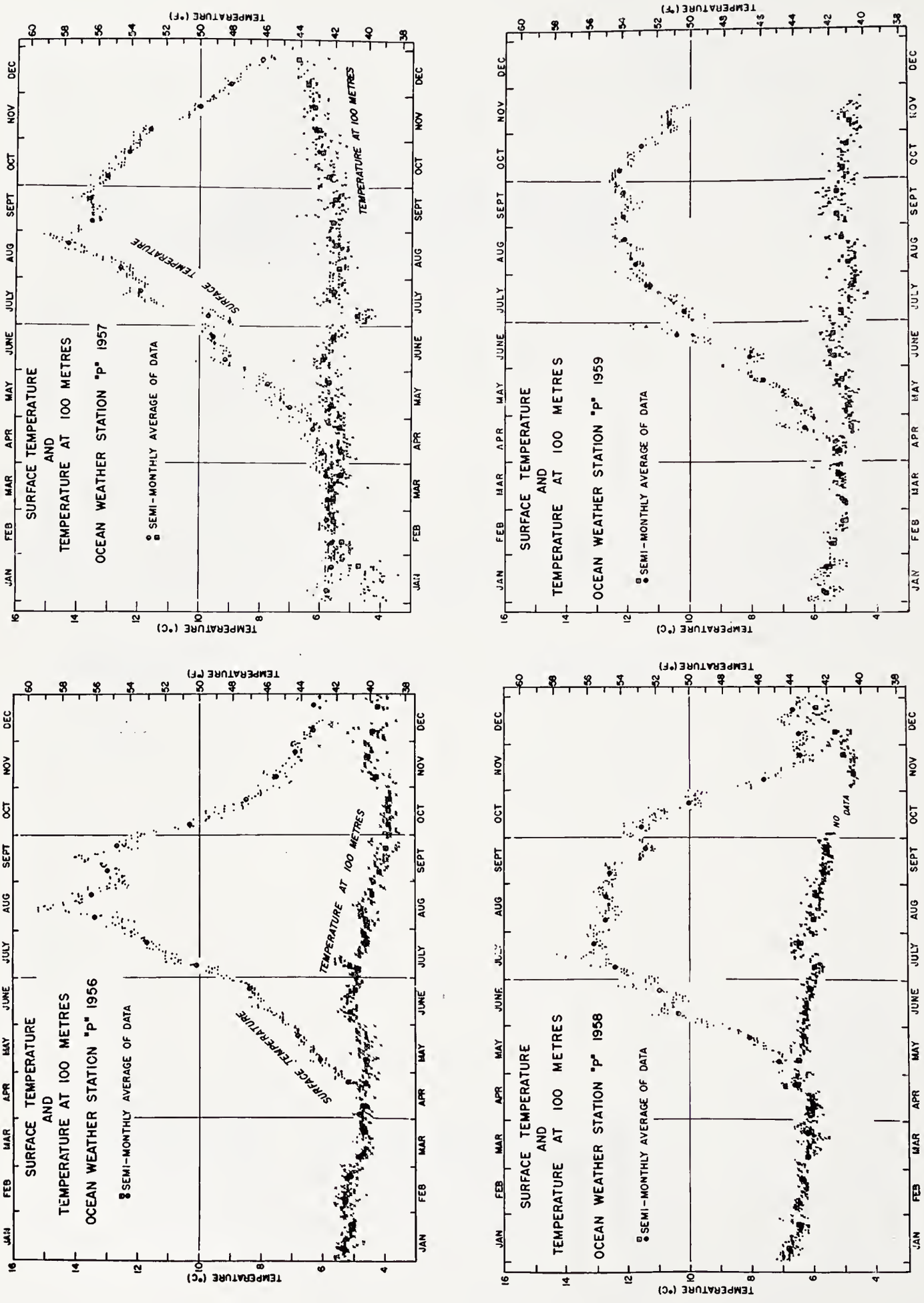

SURFACE TEMPERATURE AND TEMPERATURE AT 100 METRES
OCEAN WEATHER STATION "P" 1957
SEMI-MONTHLY AVERAGE OF DATA
SURFACE TEMPERATURE
TEMPERATURE AT 100 METRES
SURFACE TEMPERATURE AND TEMPERATURE AT 100 METRES
OCEAN WEATHER STATION "P" 1959
SEMI-MONTHLY AVERAGE OF DATA
SURFACE TEMPERATURE AND TEMPERATURE AT 100 METRES
OCEAN WEATHER STATION "P" 1956
SEMI-MONTHLY AVERAGE OF DATA
SURFACE TEMPERATURE
TEMPERATURE AT 100 METRES
SURFACE TEMPERATURE AND TEMPERATURE AT 100 METRES
OCEAN WEATHER STATION "P" 1958
SEMI-MONTHLY AVERAGE OF DATA
NO DATA
TEMPERATURE (°C)
TEMPERATURE (°F)
JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC

FIGURE 40. Temperatures at the surface and 100 metres depth, Ocean Station "P", 1956 through 1959.

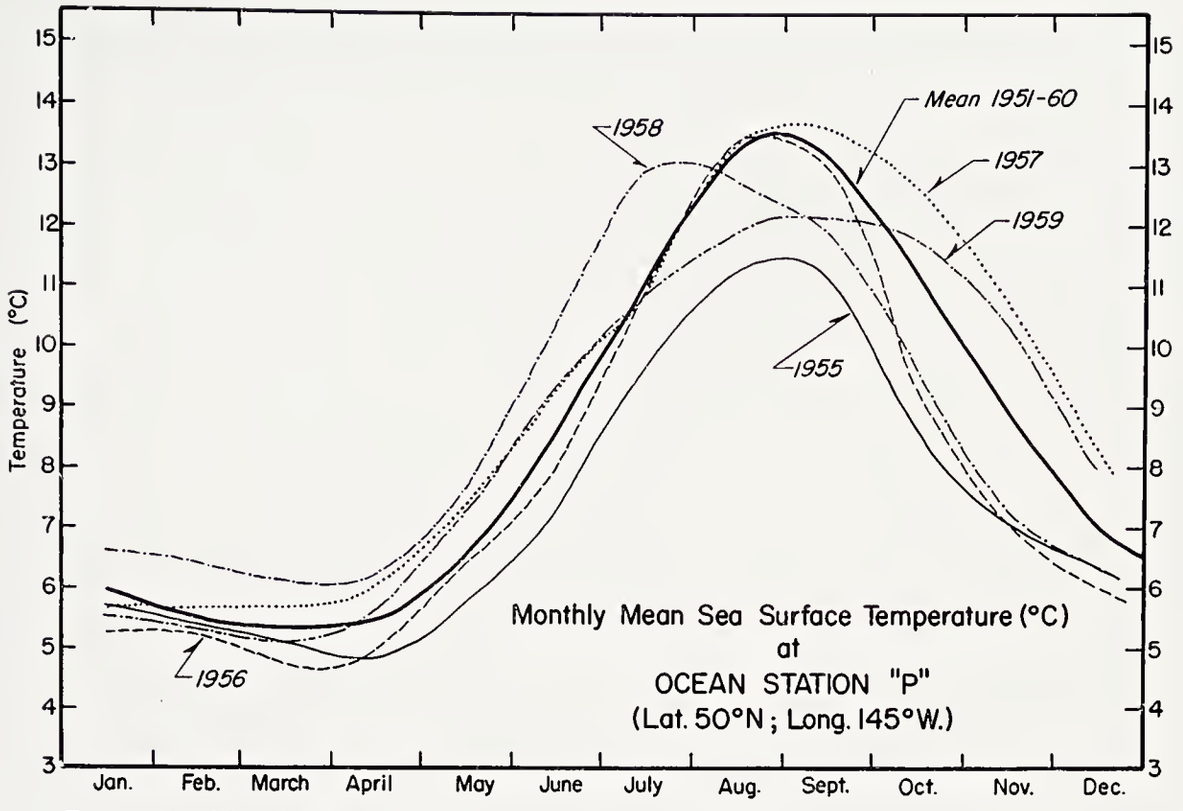


FIGURE 41. Monthly mean sea surface temperature at Ocean Station "P", 1955 through 1959.

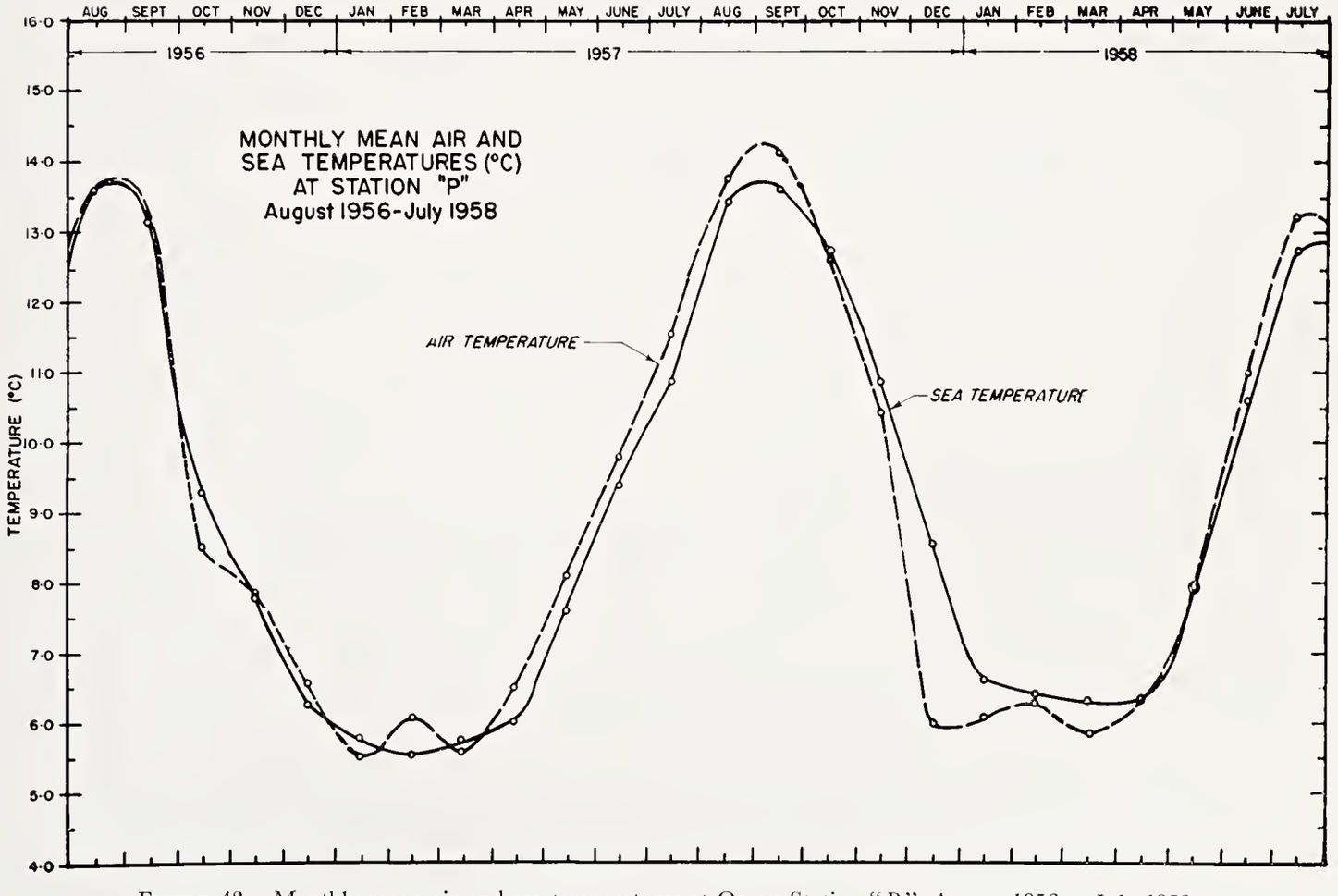

AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY
1956
1957
1958
MONTHLY MEAN AIR AND
SEA TEMPERATURES (°C)
AT STATION "P"
August 1956-July 1958
AIR TEMPERATURE
SEA TEMPERATURE
TEMPERATURE (°C)

FIGURE 42. Monthly mean air and sea temperatures at Ocean Station "P", August 1956 to July 1958.

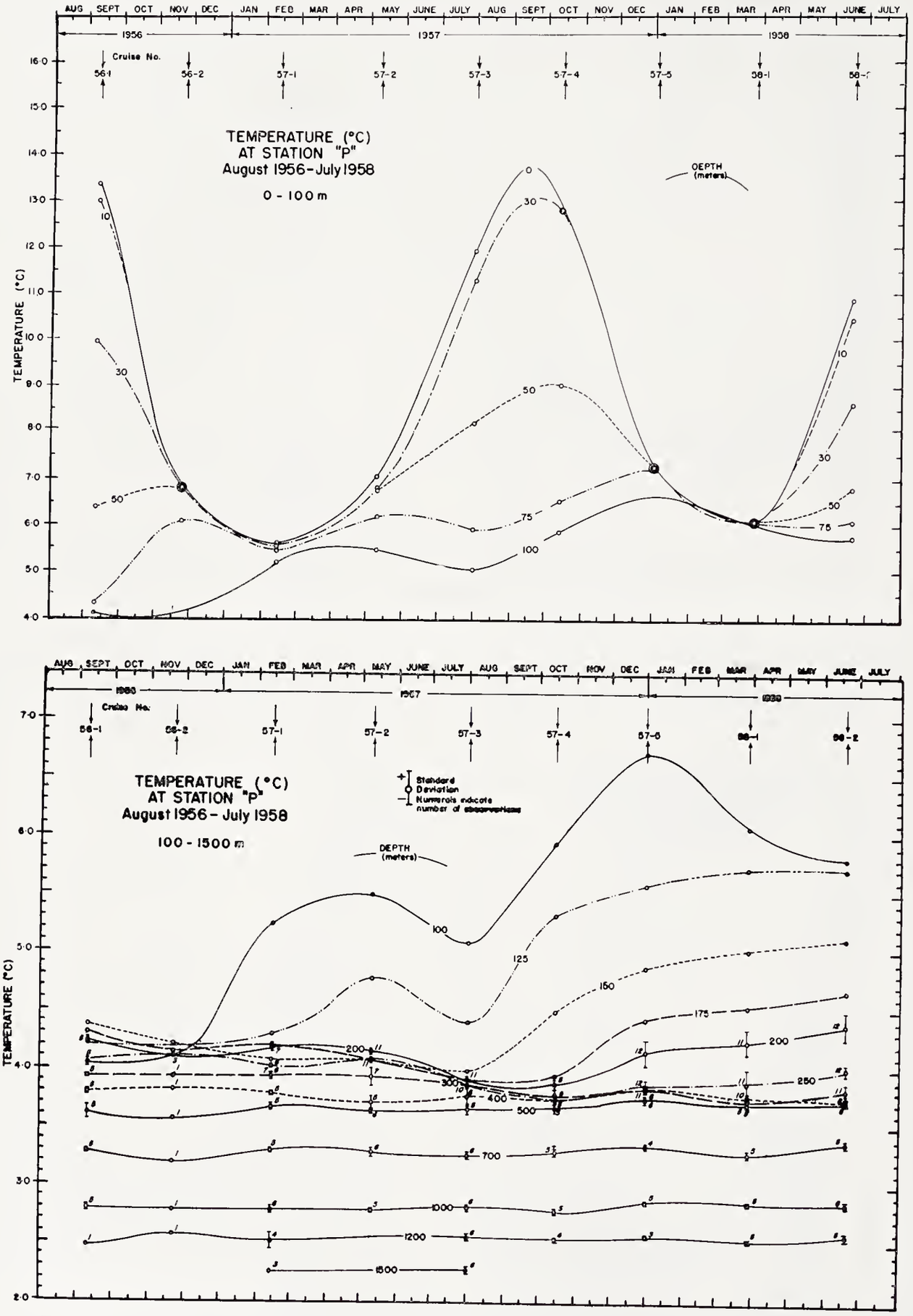


FIGURE 43. Values of temperature at selected depths at Ocean Station "P", August 1956 to July 1958 (Tabata, 1961) (std. dev. not shown at 10 to 175 m.).

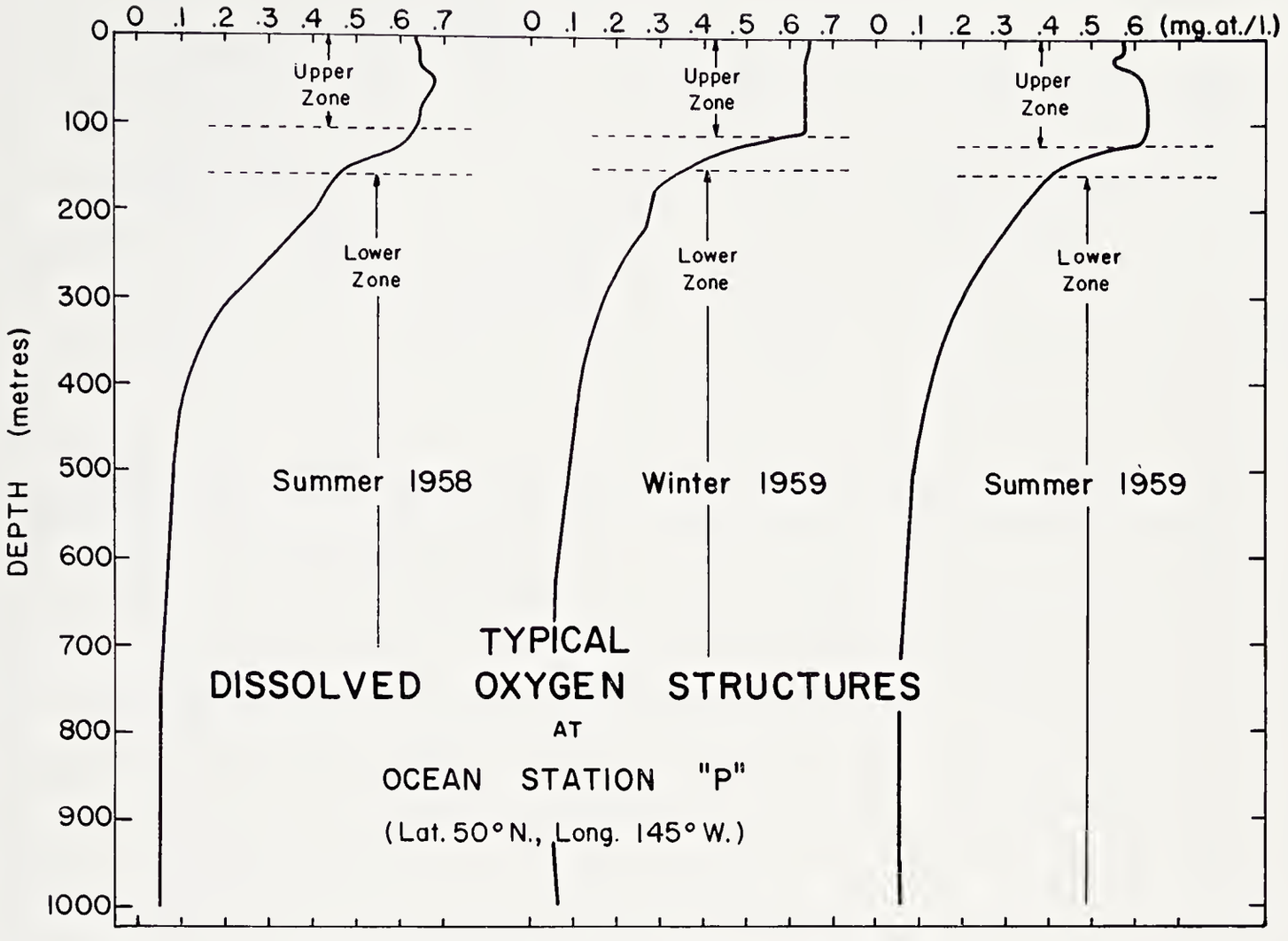


FIGURE 44. Typical dissolved oxygen structures at Ocean Station "P".

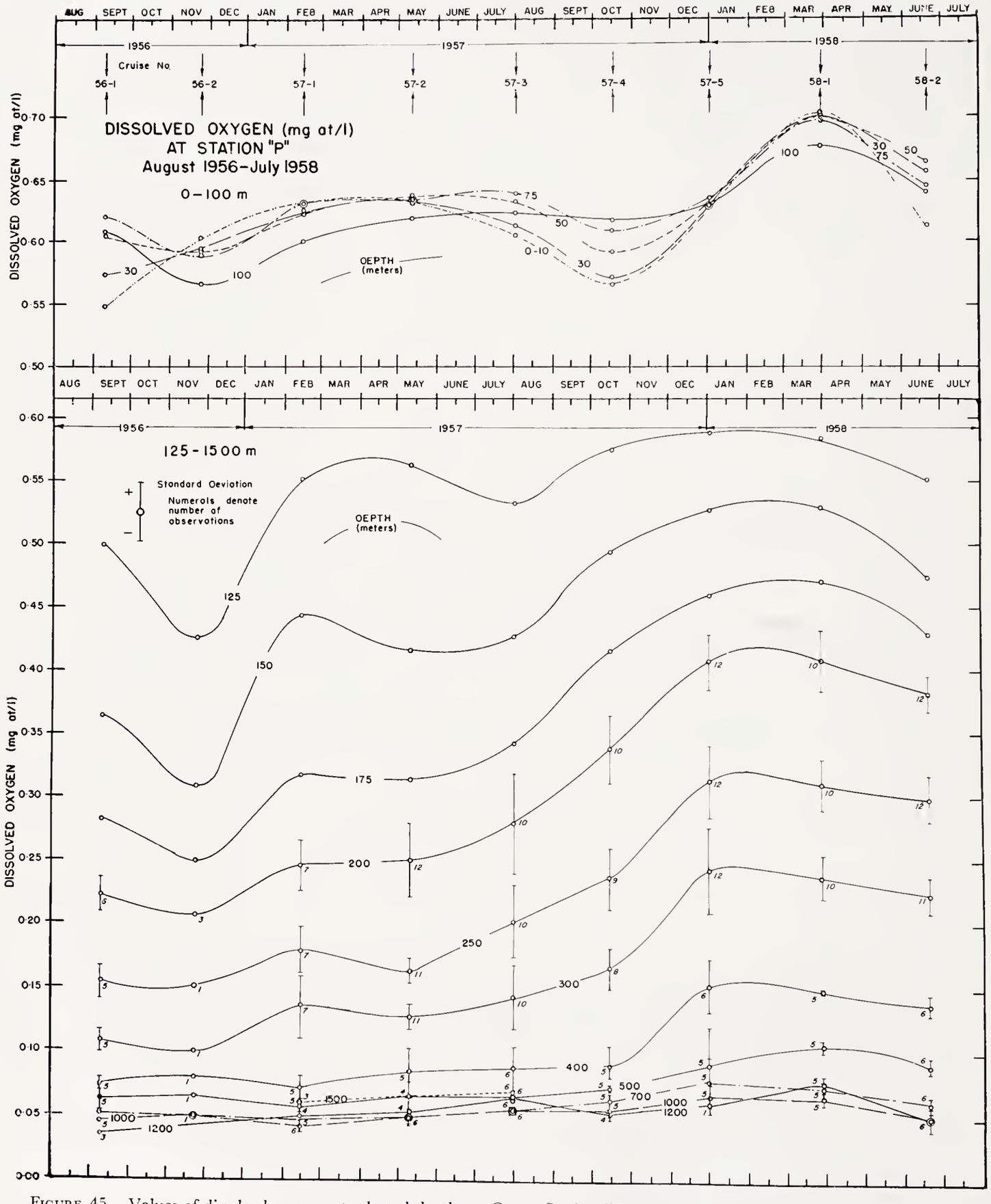


FIGURE 45. Values of dissolved oxygen at selected depths at Ocean Station "P", August 1956 to July 1958 (Tabata, 1961) (std. dev. not shown at 10 to 175 m.).

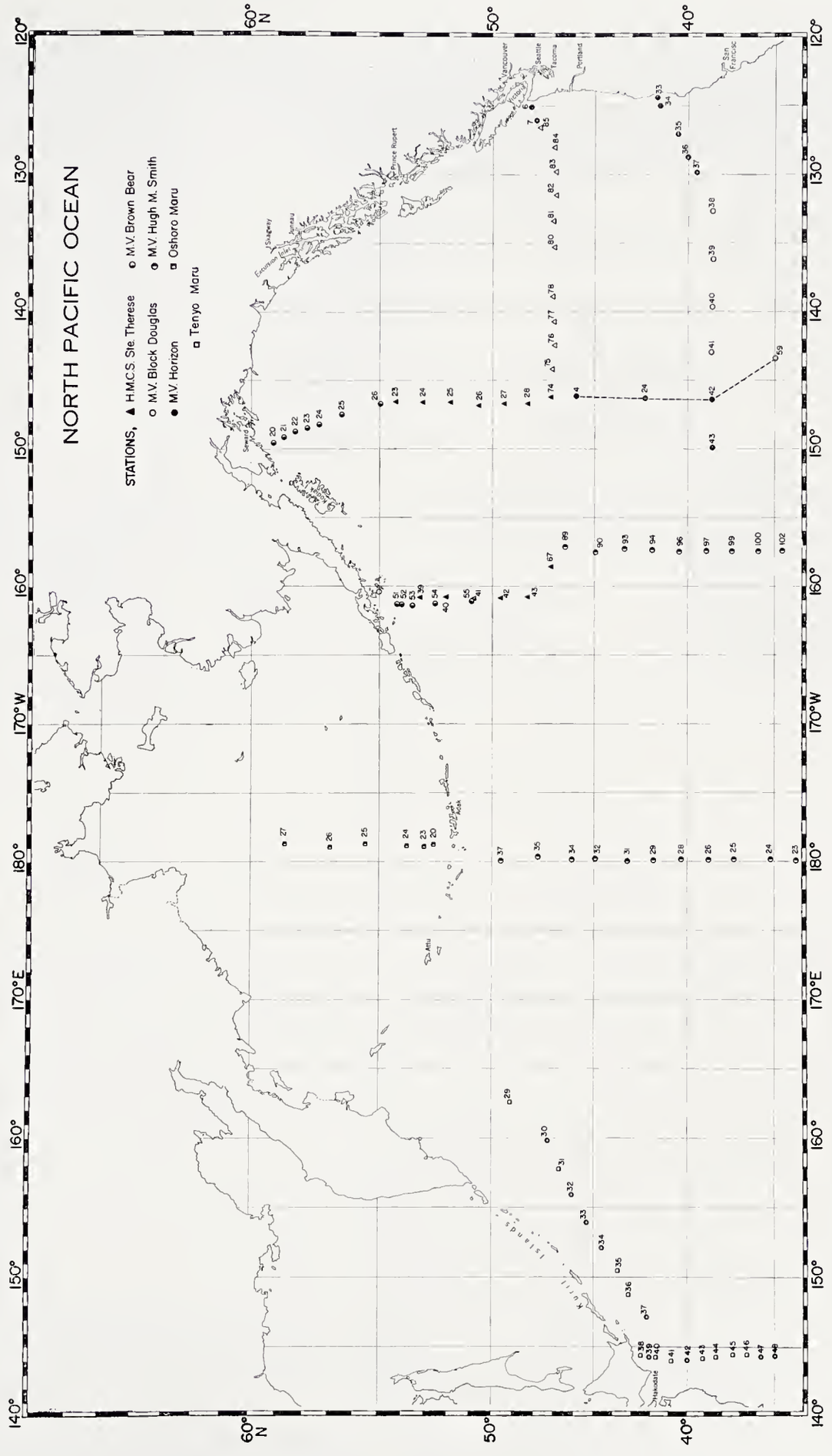


FIGURE 46. Locations of vertical sections, summer 1955.

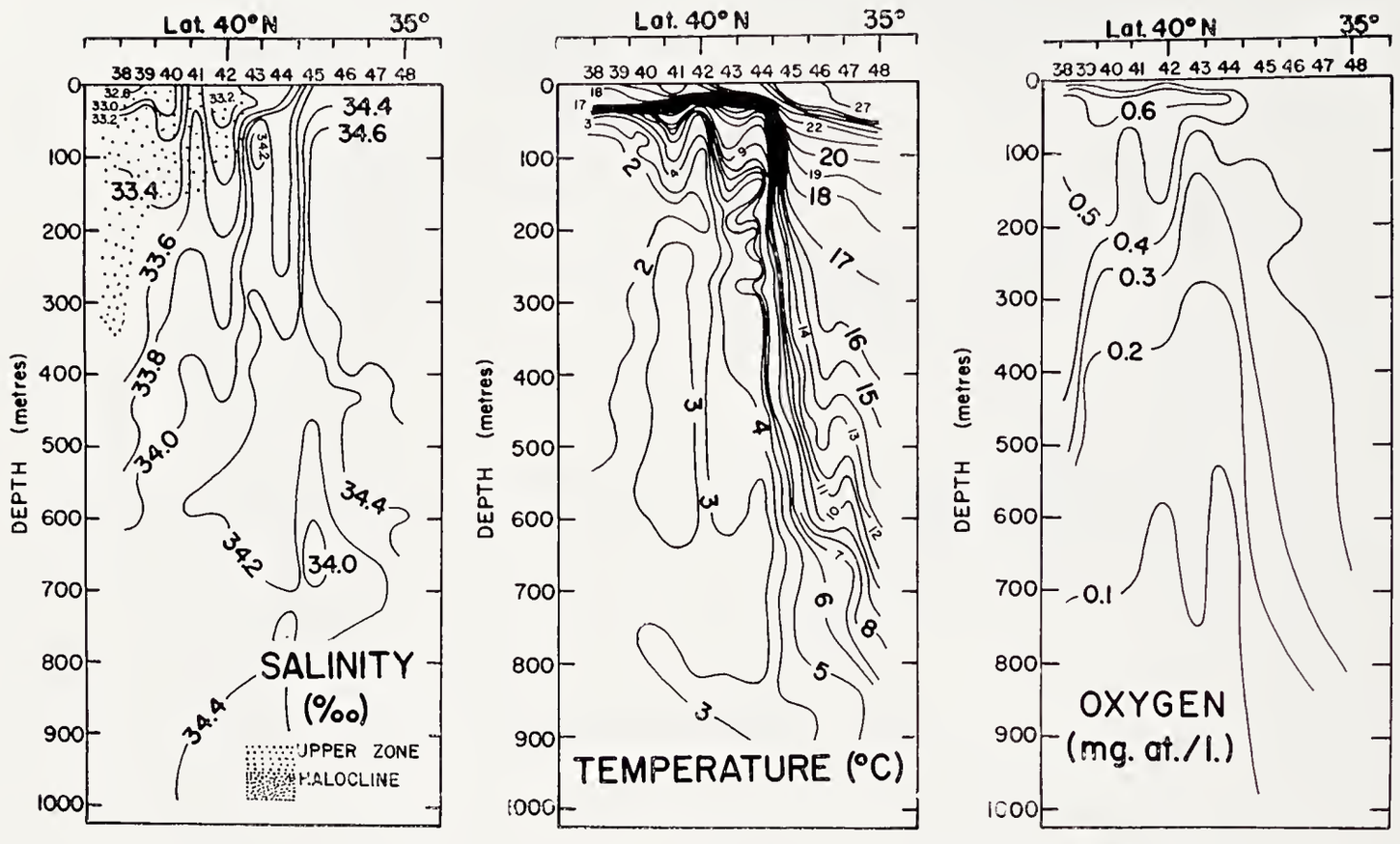


FIGURE 47. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 145°E., summer 1955.

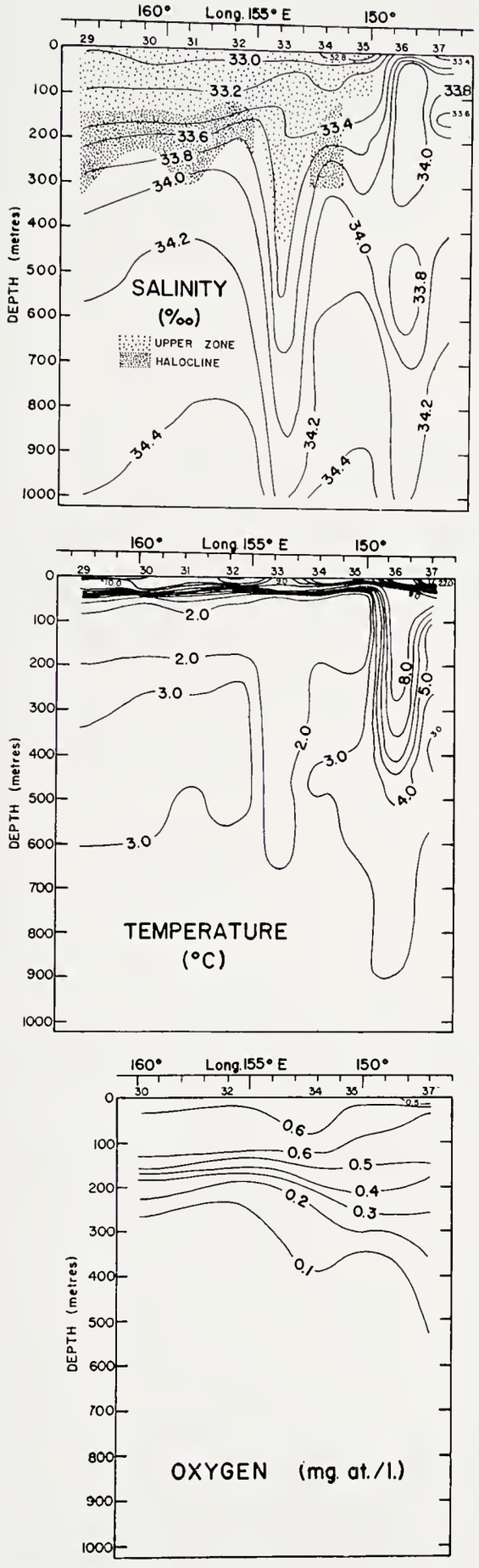


FIGURE 48. Vertical sections of salinity, temperature and dissolved oxygen along Kuril Islands, summer 1955.

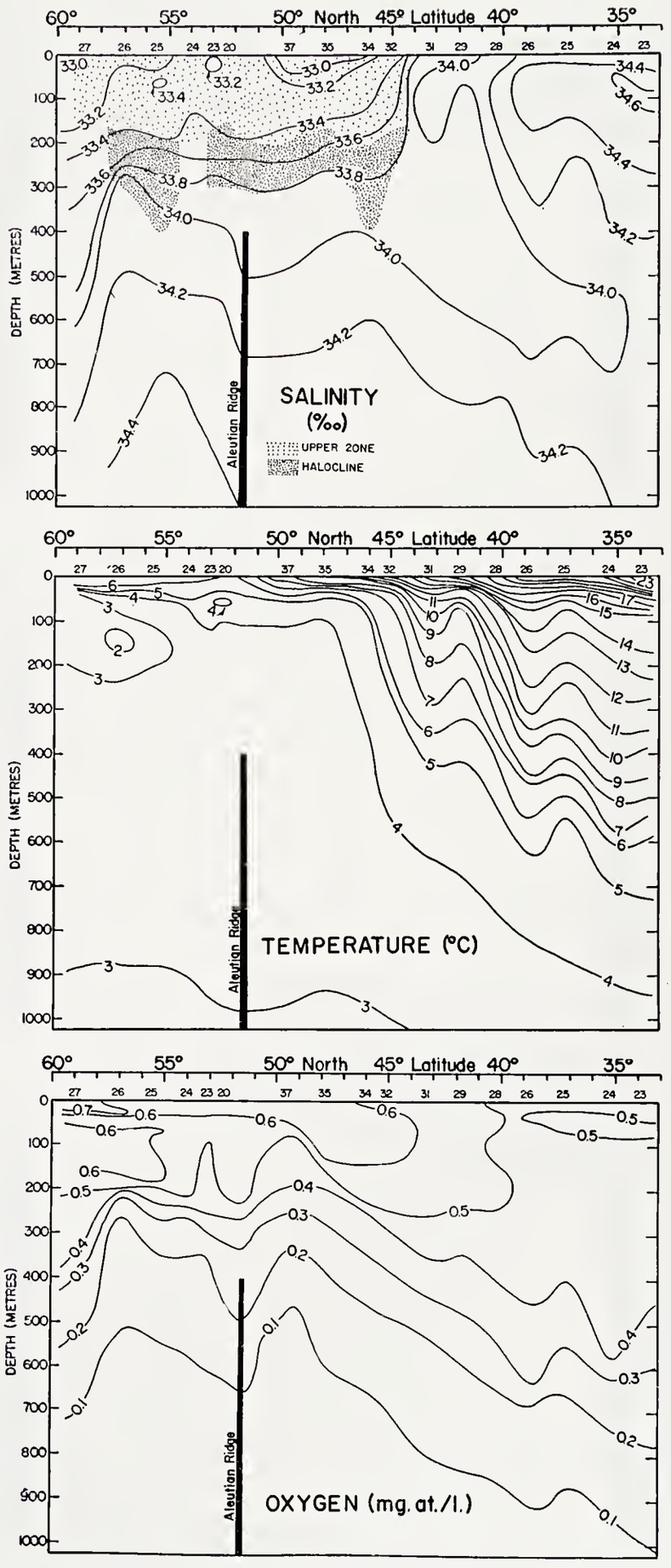


FIGURE 49. Vertical sections of salinity, temperature and dissolved oxygen along long. 180°, summer 1955.

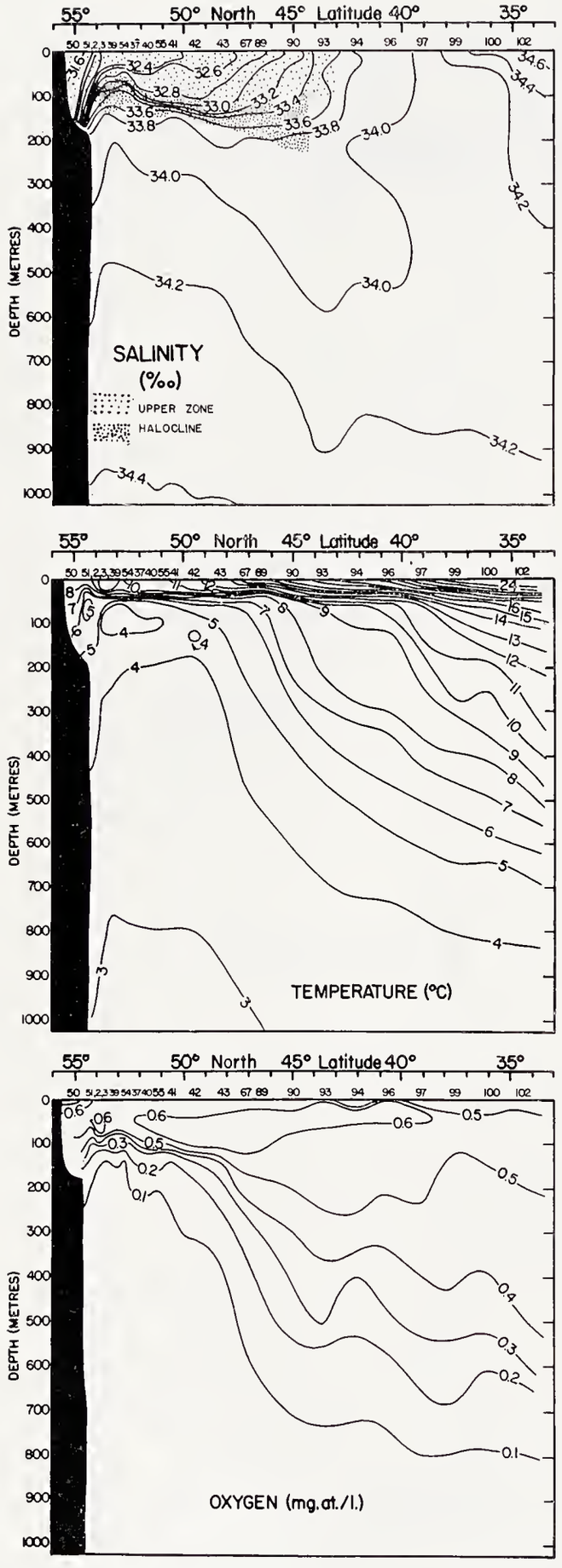


FIGURE 50. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 160°W., summer 1955.

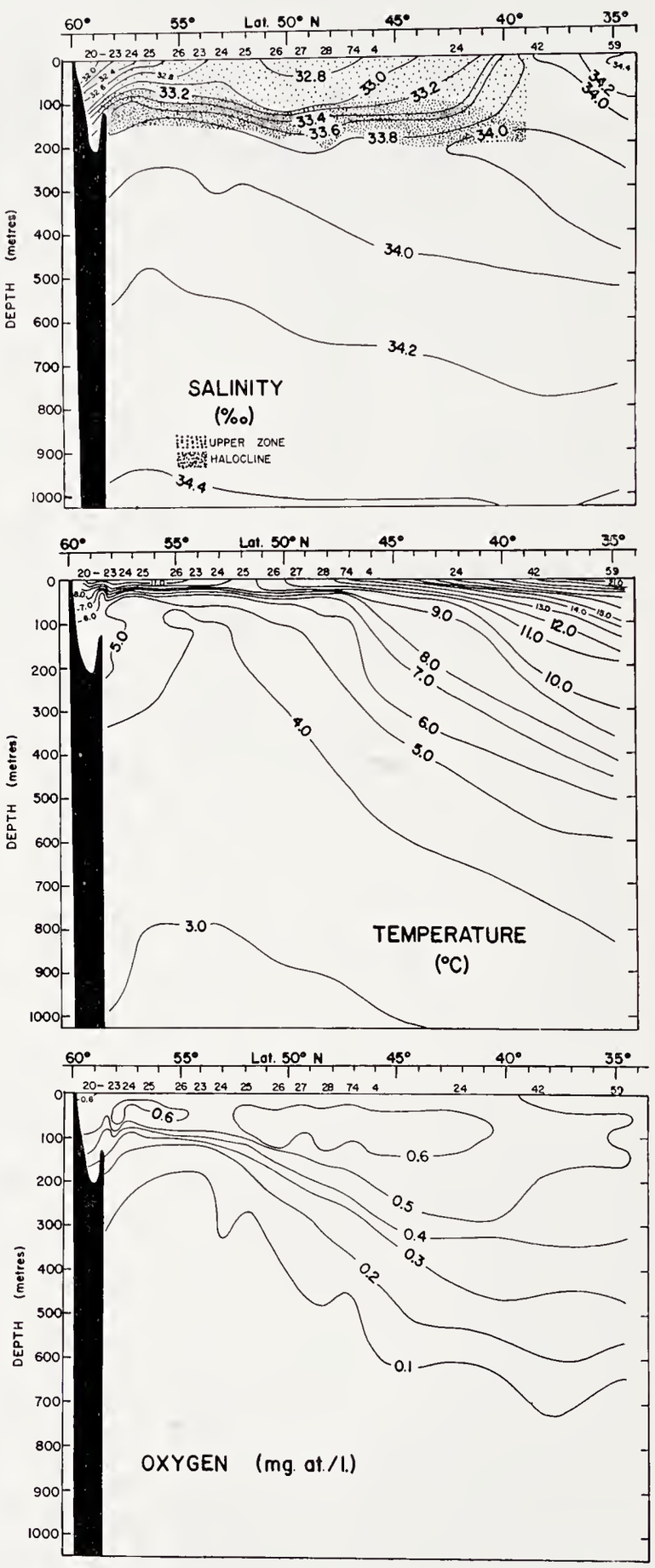


FIGURE 51. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 148°W., summer 1955.

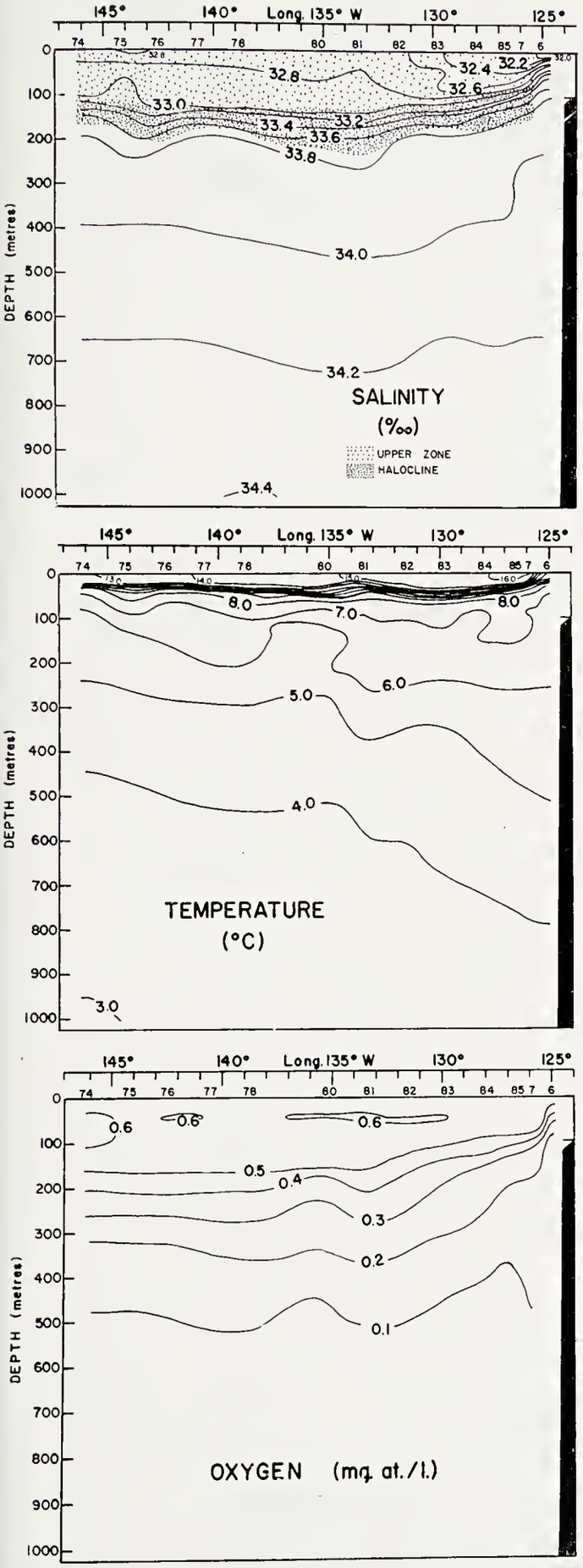


FIGURE 52. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 47°N., summer 1955.

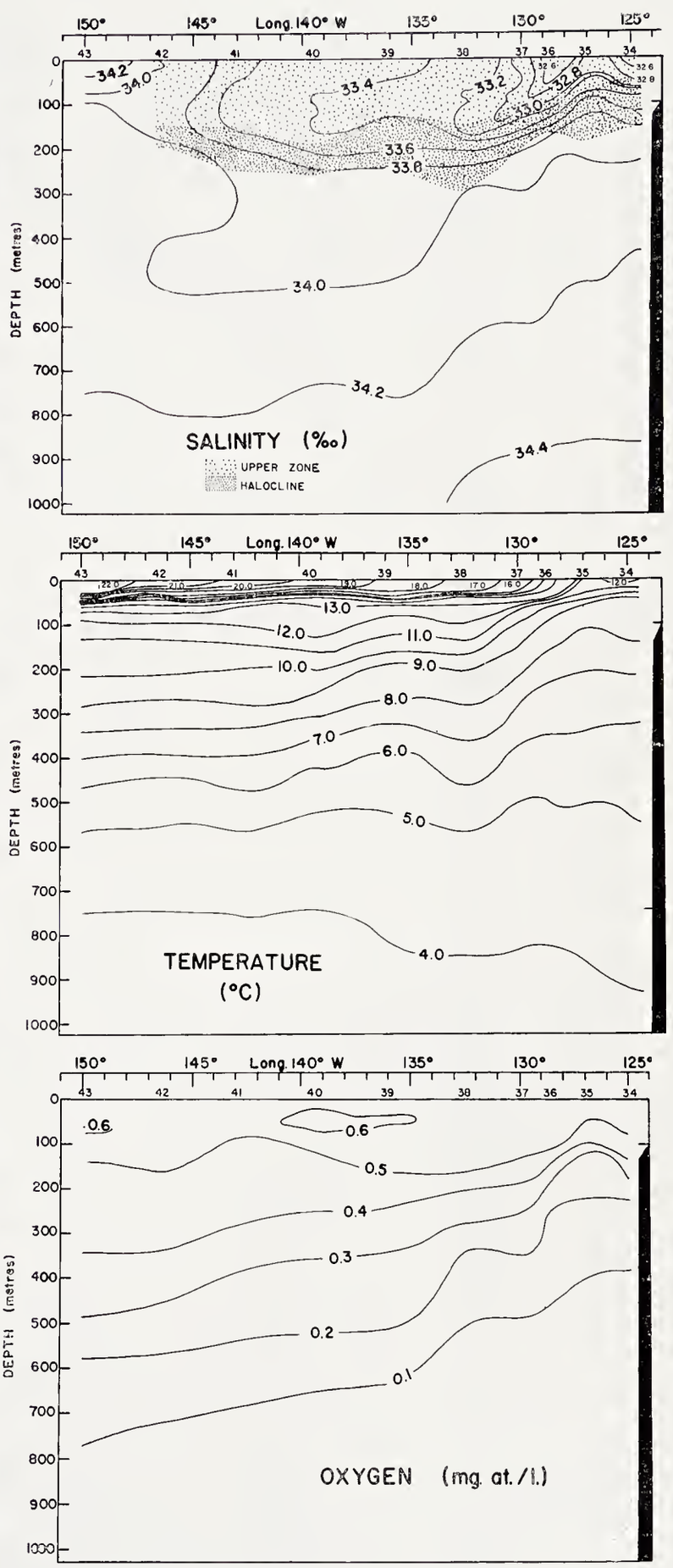


FIGURE 53. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 39°N., summer 1955.

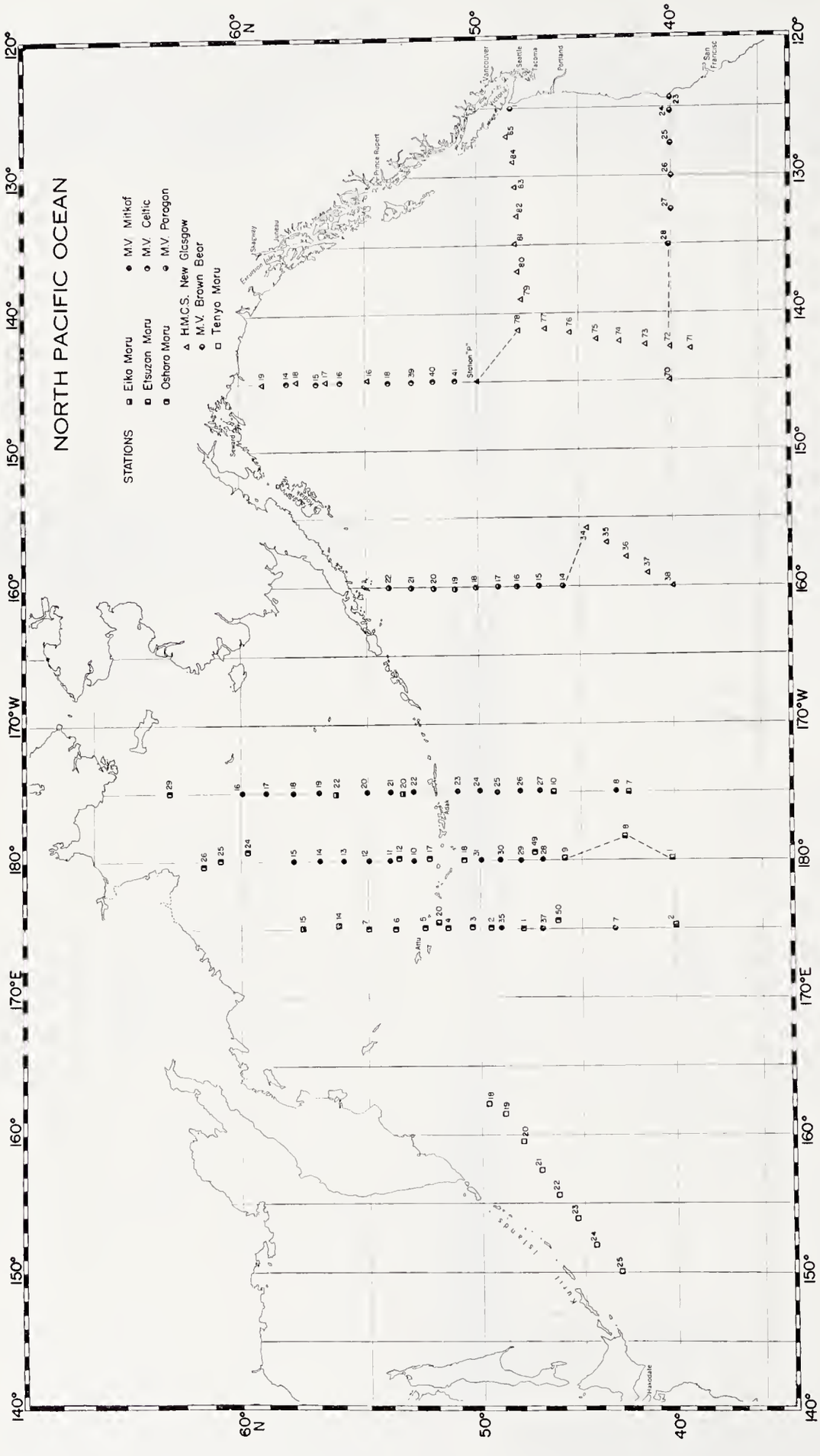


FIGURE 54. Locations of vertical sections, summer 1956.

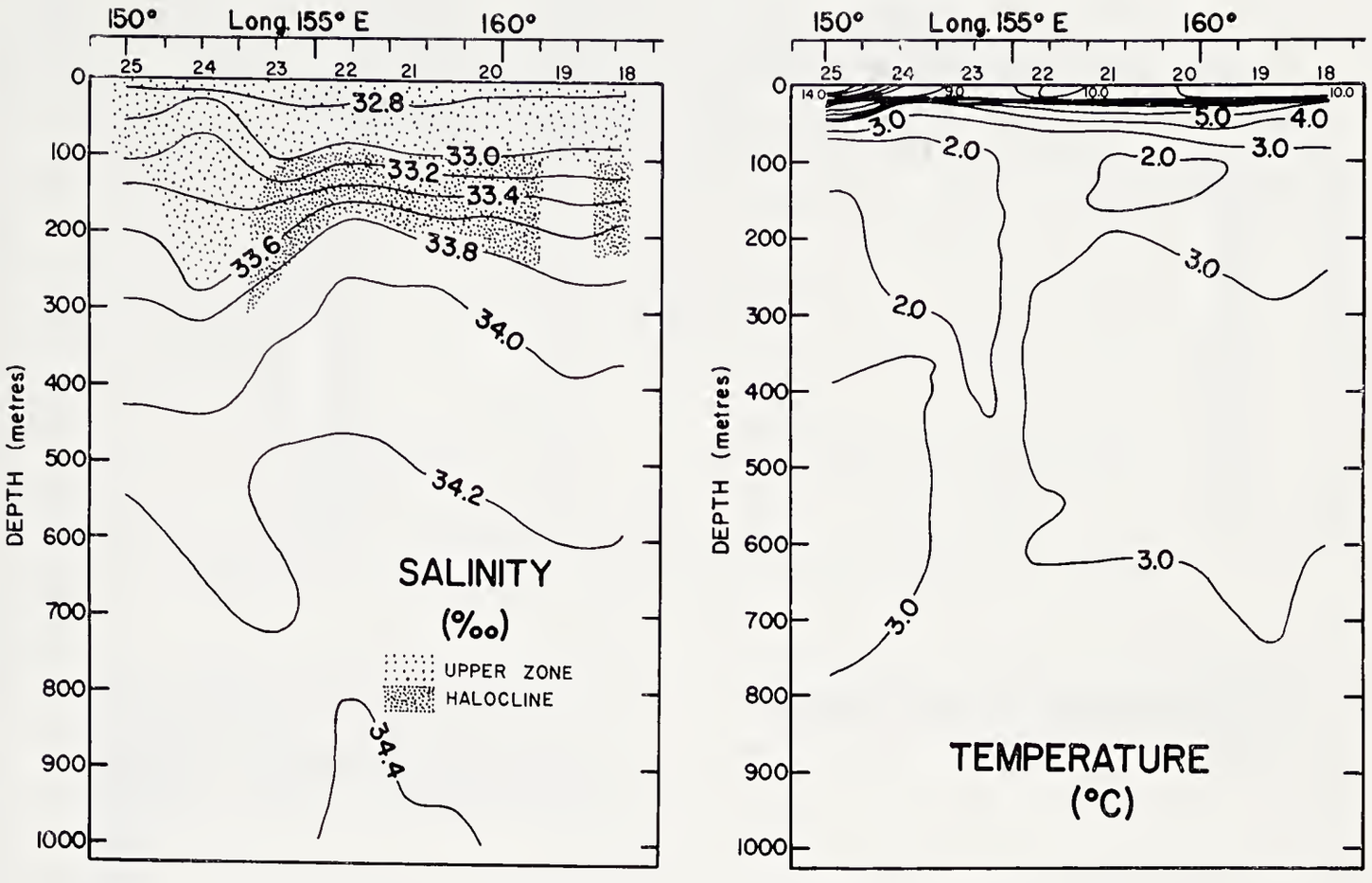


FIGURE 55. Vertical sections of salinity and temperature along Kuril Islands, summer 1956.

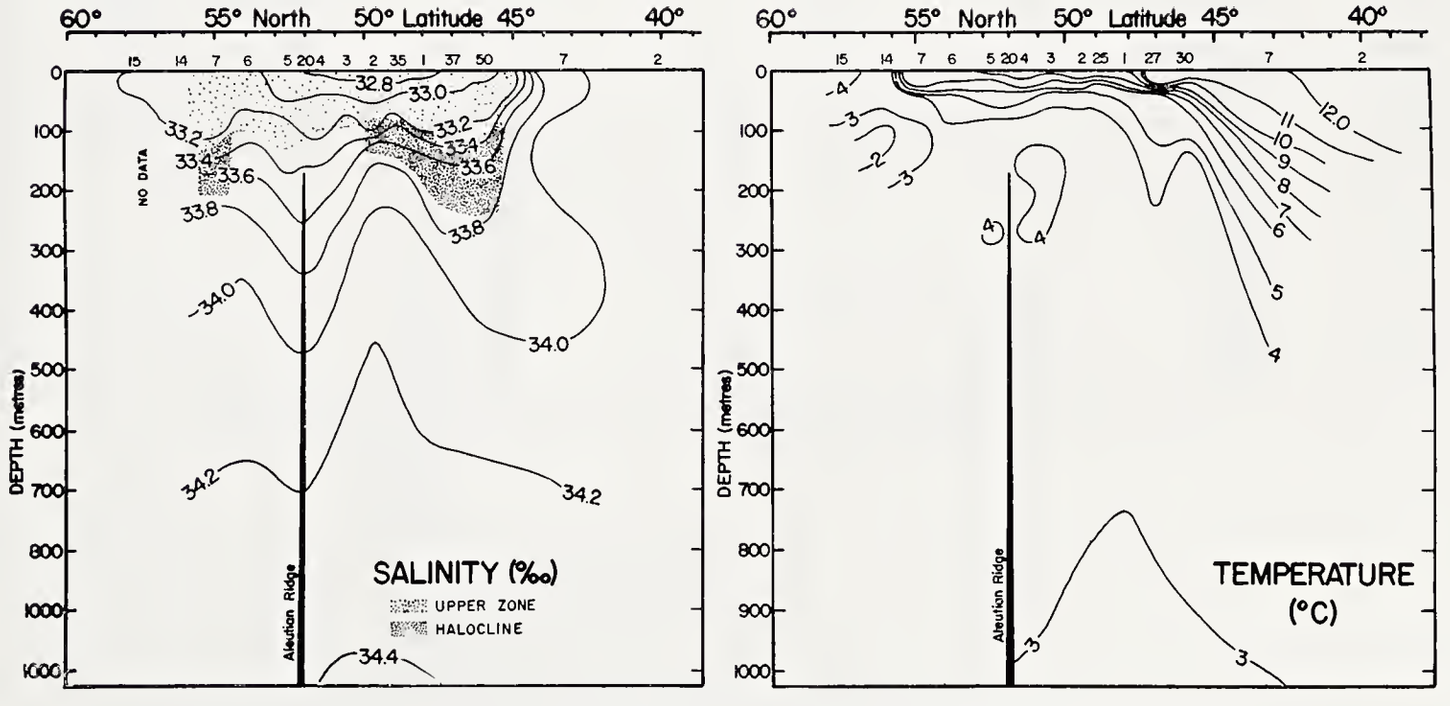


FIGURE 56. Vertical sections of salinity and temperature along long. 175°E., summer 1956.

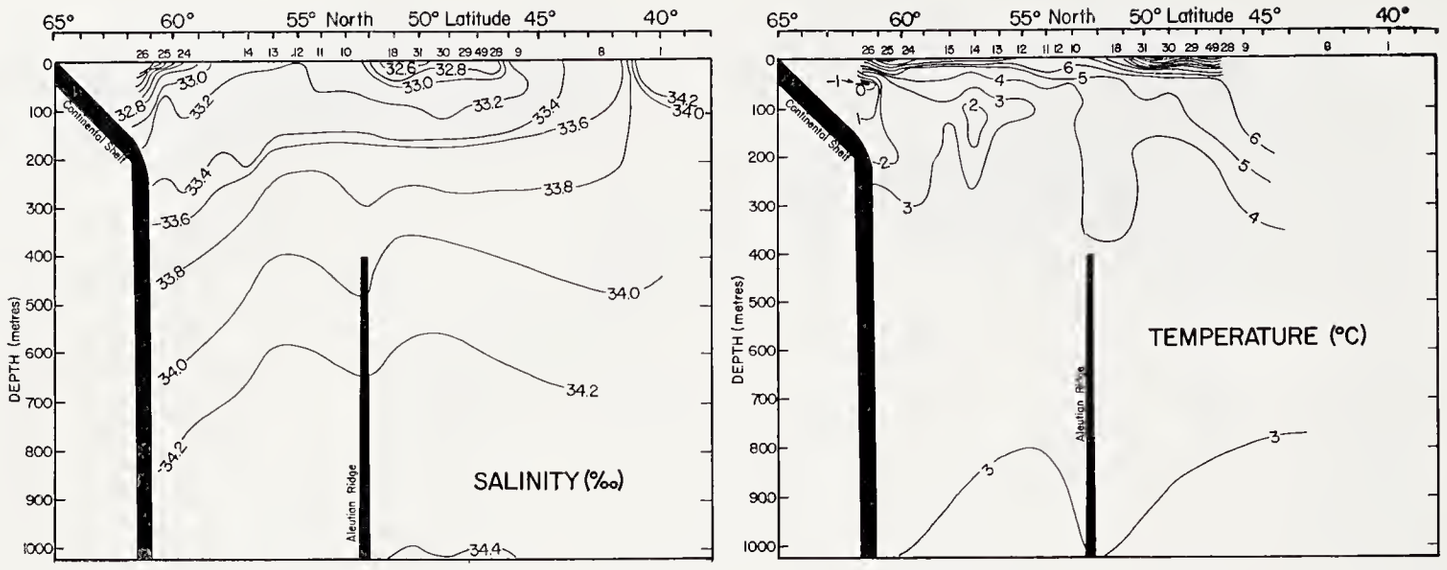


FIGURE 57. Vertical sections of salinity and temperature along long. 180°, summer 1956.

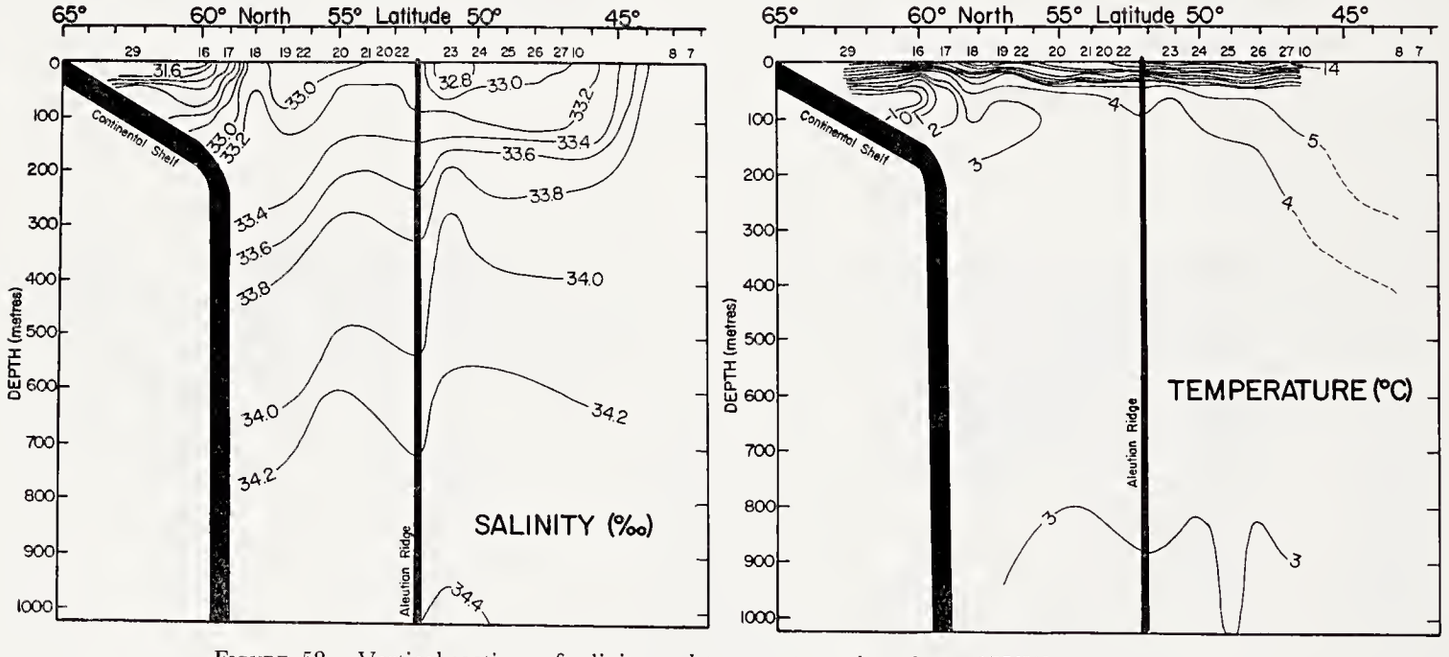


FIGURE 58. Vertical sections of salinity and temperature along long. 175°W., summer 1956.

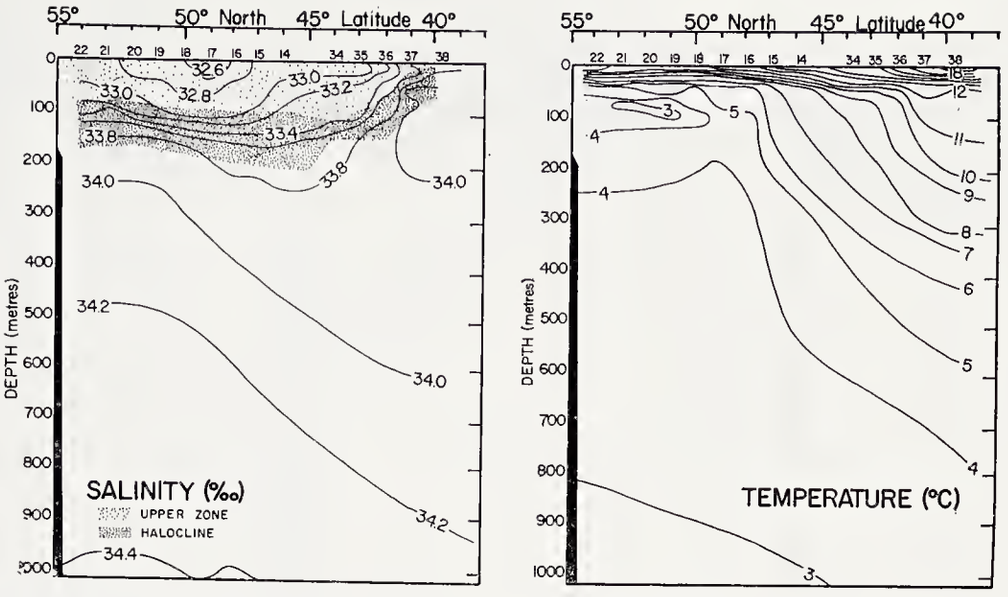


FIGURE 59. Vertical sections of salinity and temperature along long. 160°W., summer 1956.

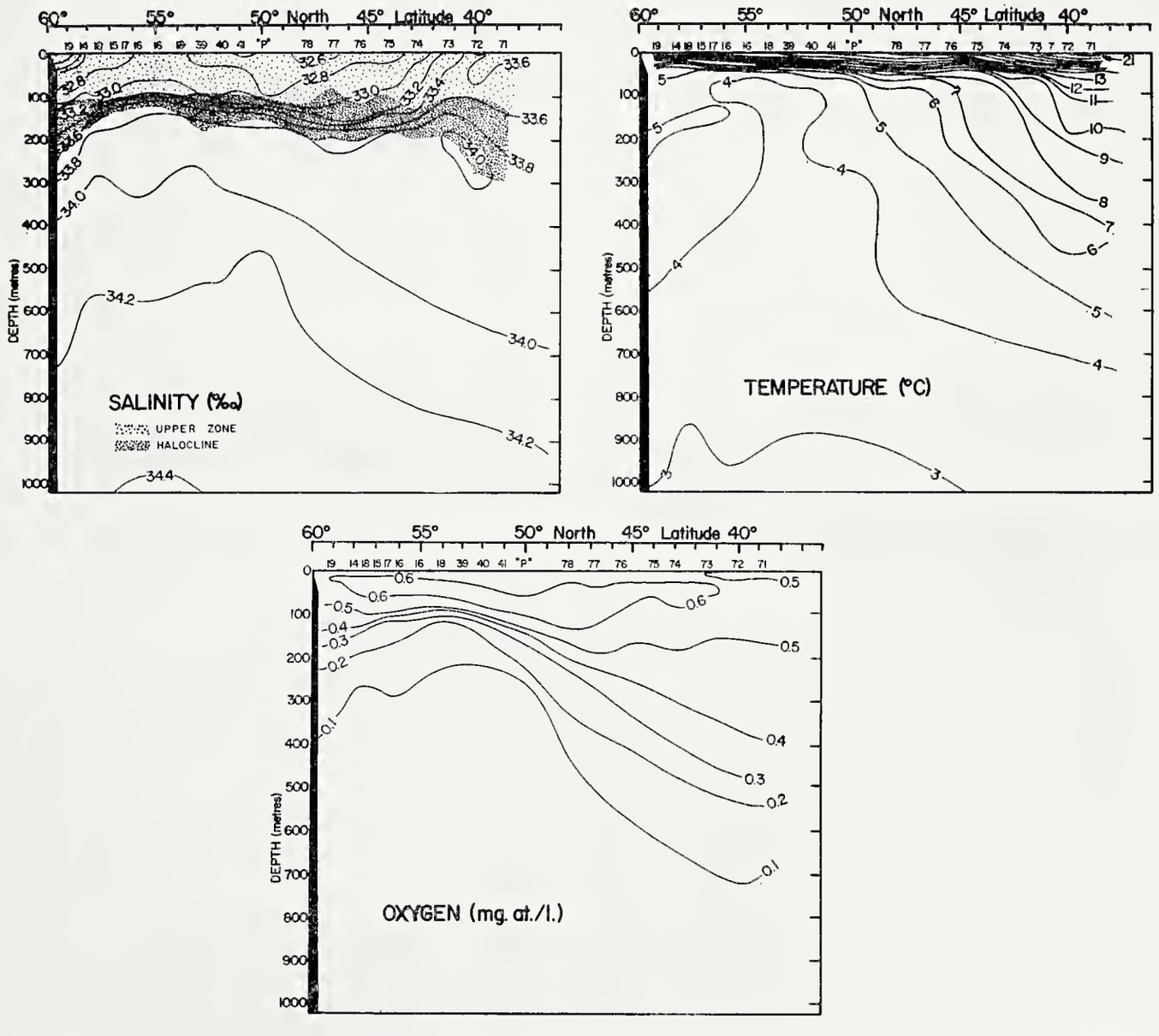


FIGURE 60. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 145°W., summer 1956.

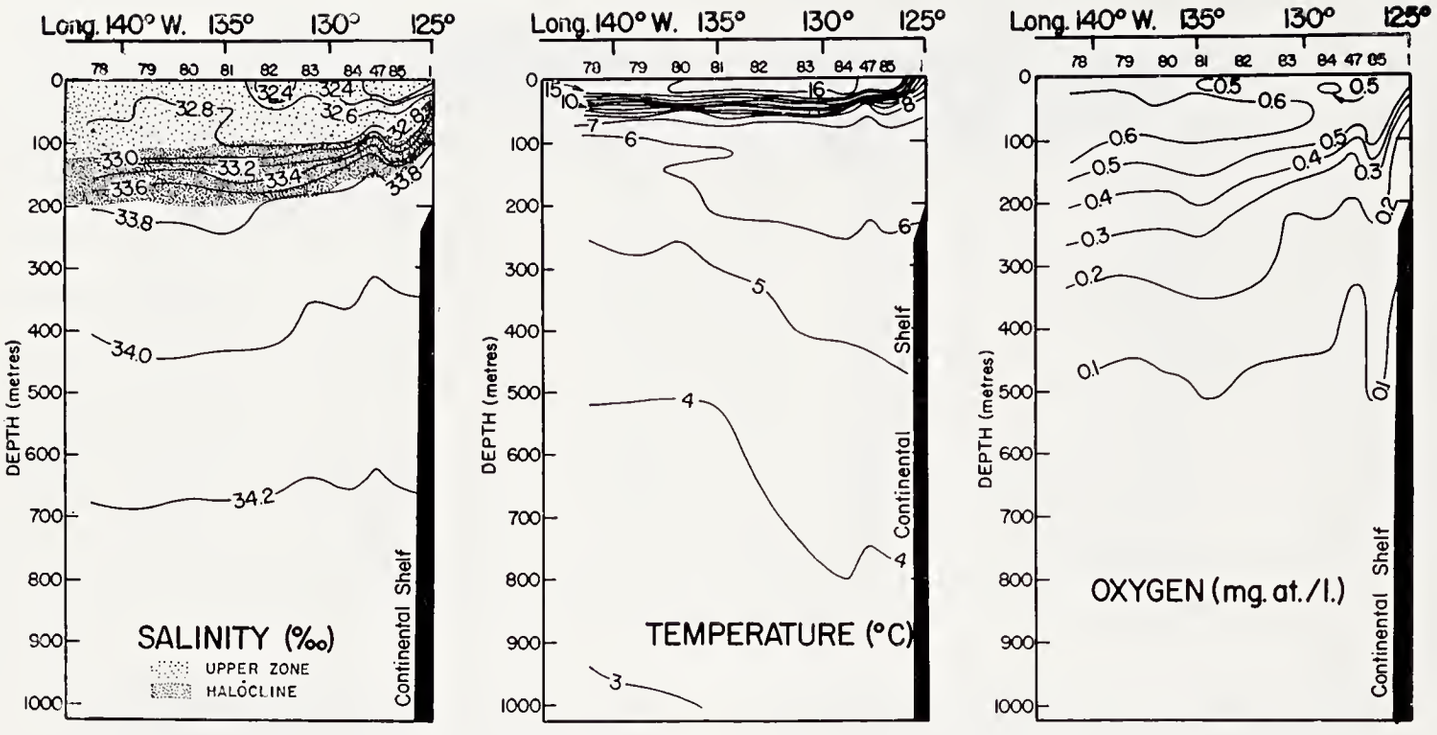


FIGURE 61. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 48°N., summer 1956.

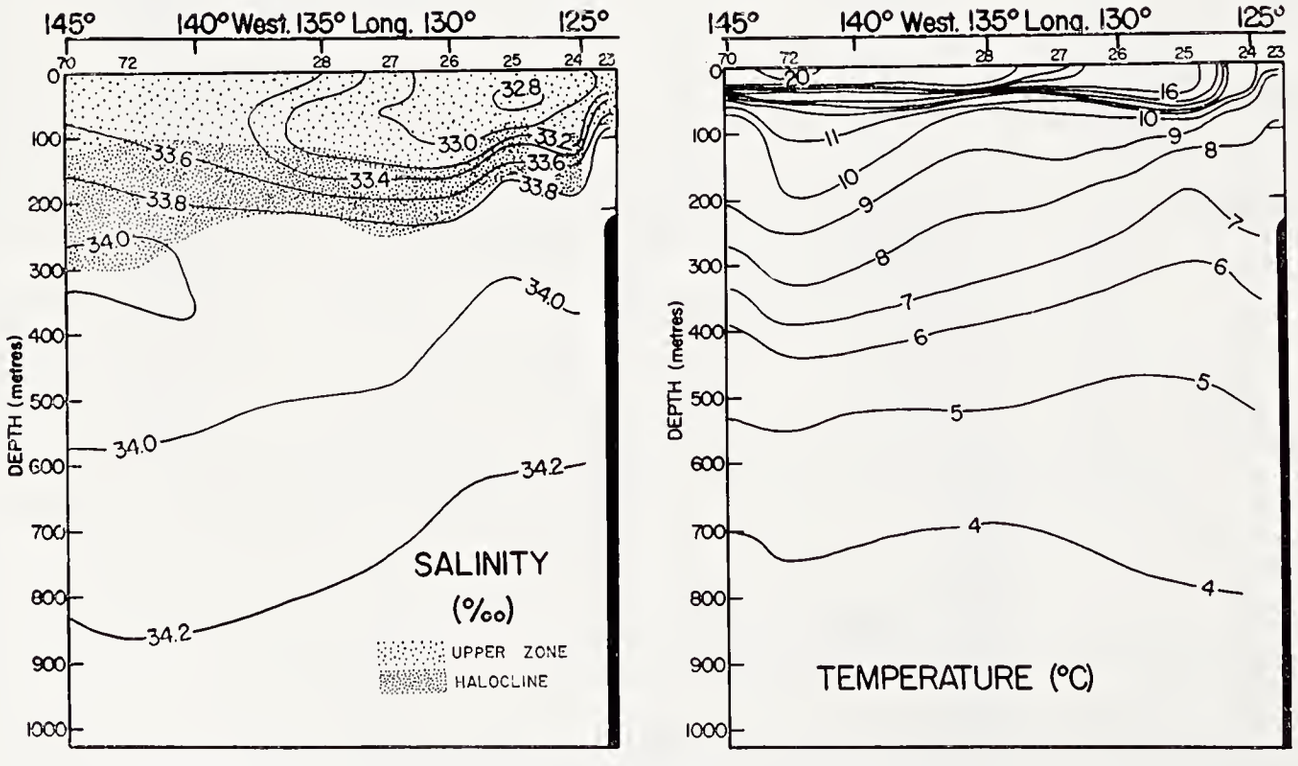


FIGURE 62. Vertical sections of salinity and temperature along lat. 40°N., summer 1956.

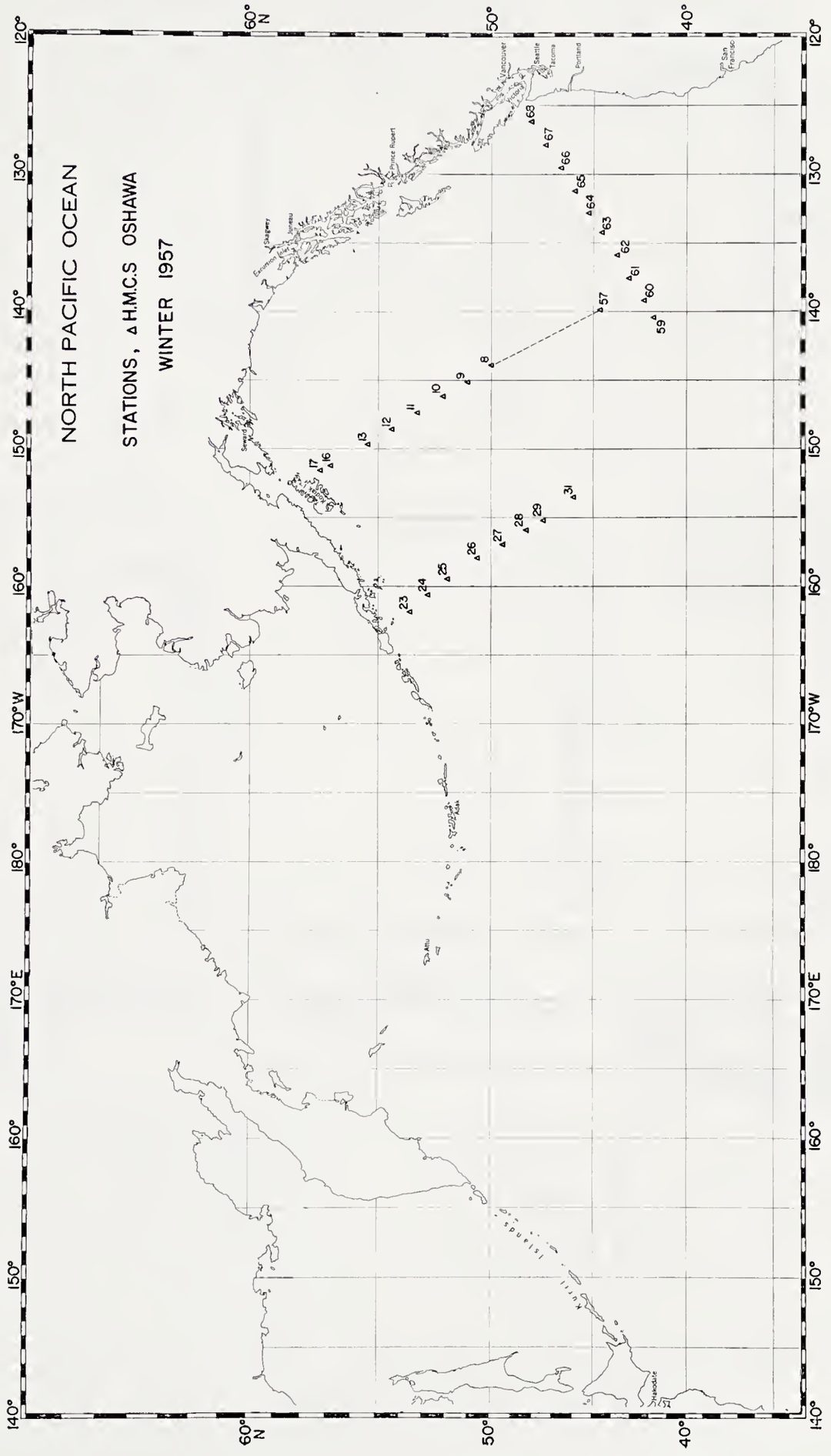


FIGURE 63. Locations of vertical sections, winter 1957.

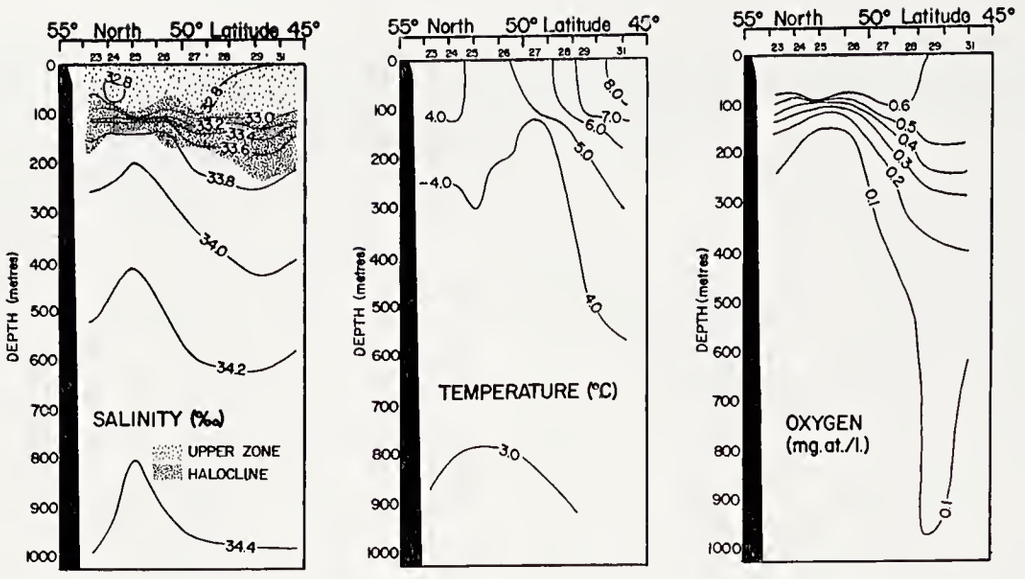


FIGURE 64. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 157°W., winter 1957.

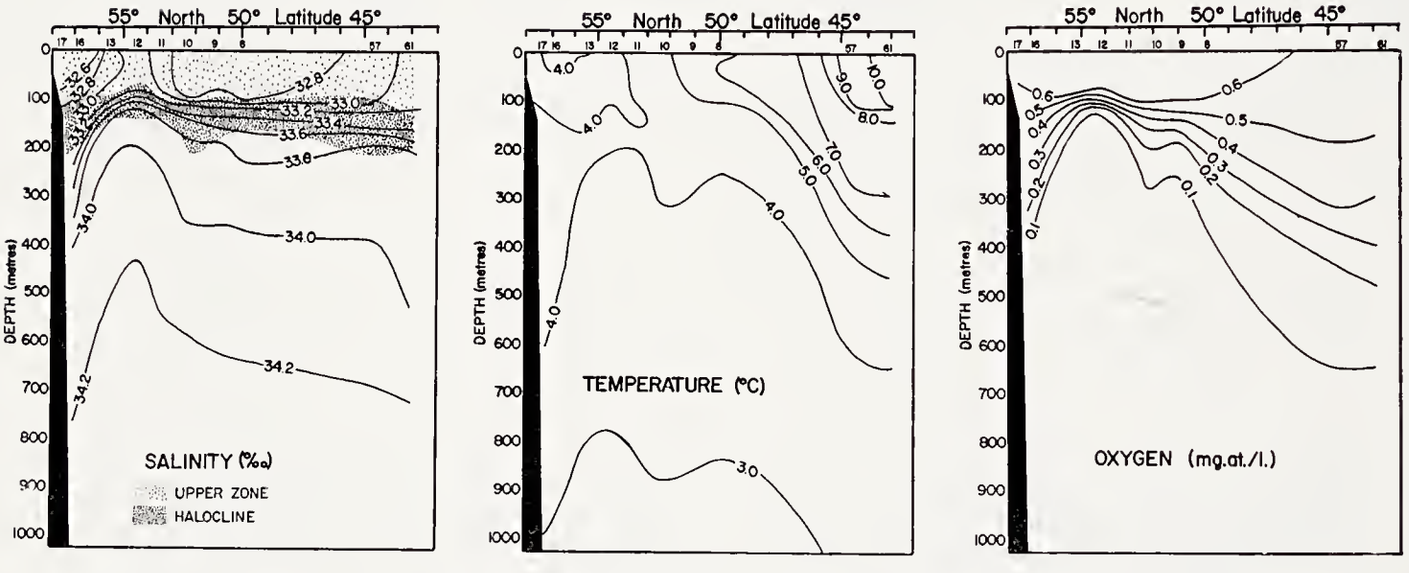


FIGURE 65. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 147°W., winter 1957.

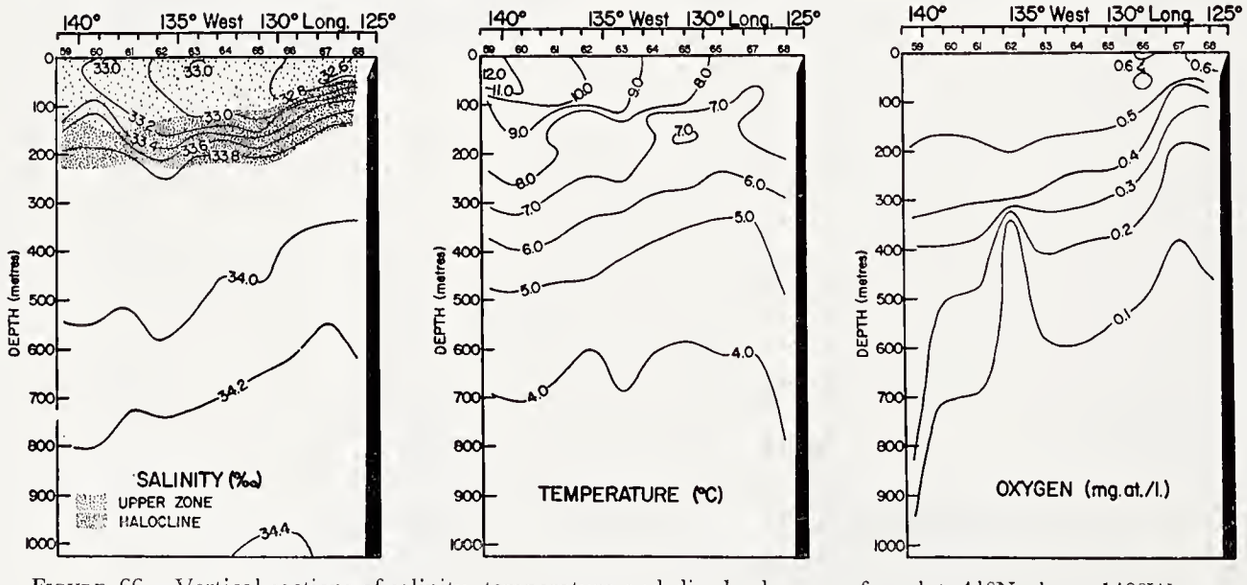


FIGURE 66. Vertical sections of salinity, temperature and dissolved oxygen from lat. 41°N., long. 140°W. to Vancouver Island, winter 1957.

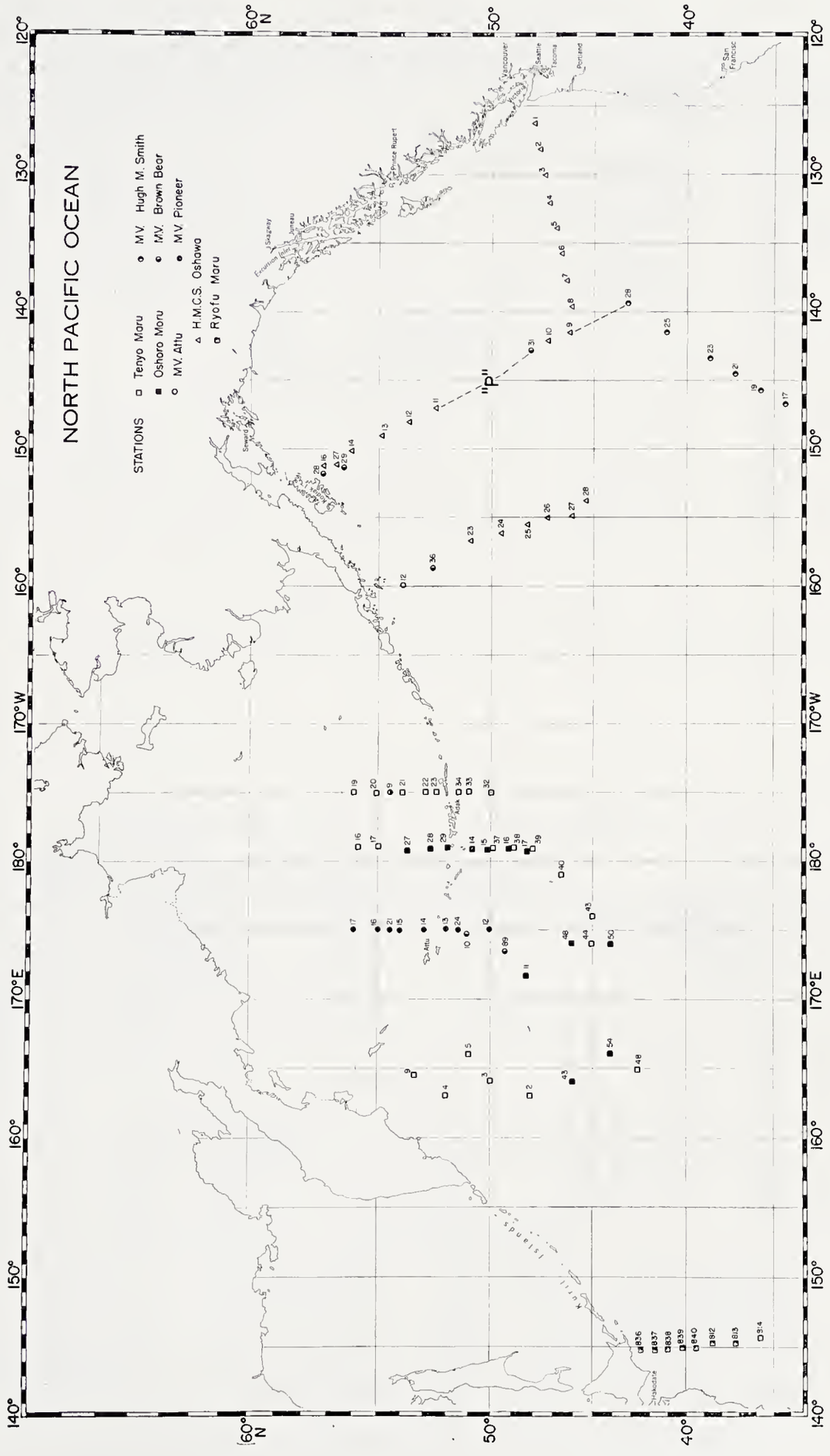


FIGURE 67. Locations of vertical sections, summer 1957.

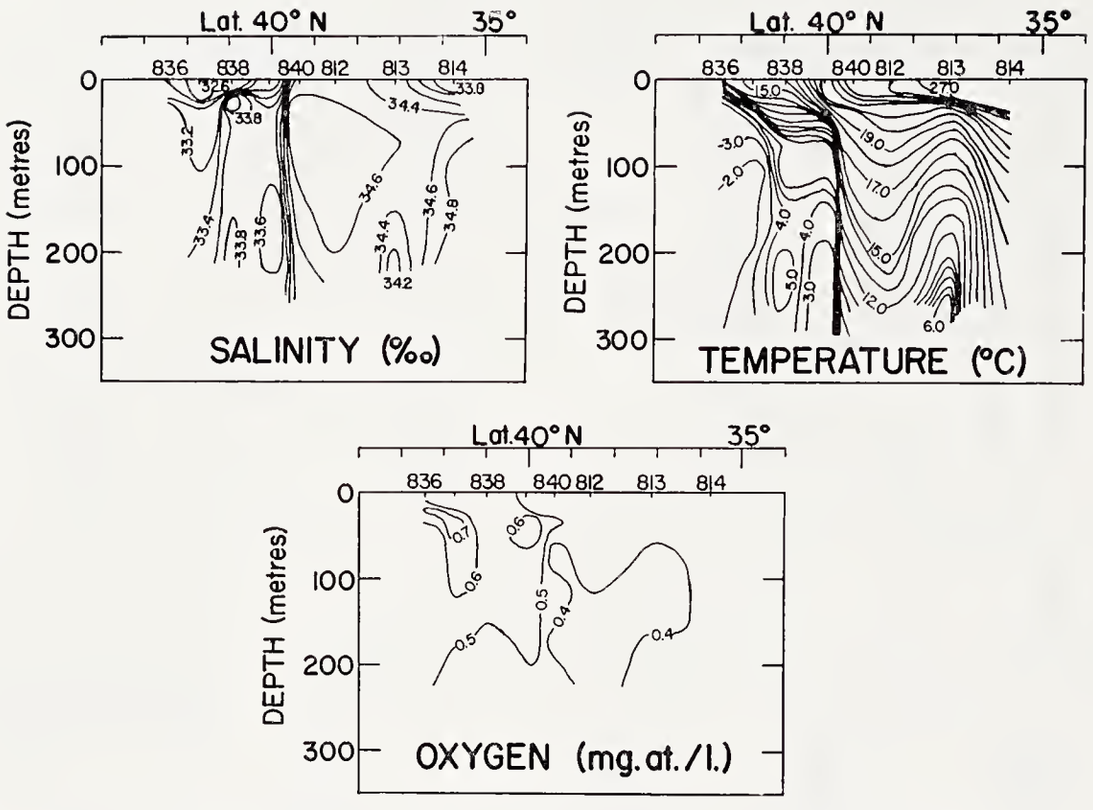


FIGURE 68. Vertical sections of salinity, temperature and dissolved oxygen along long. 145°E., summer 1957.

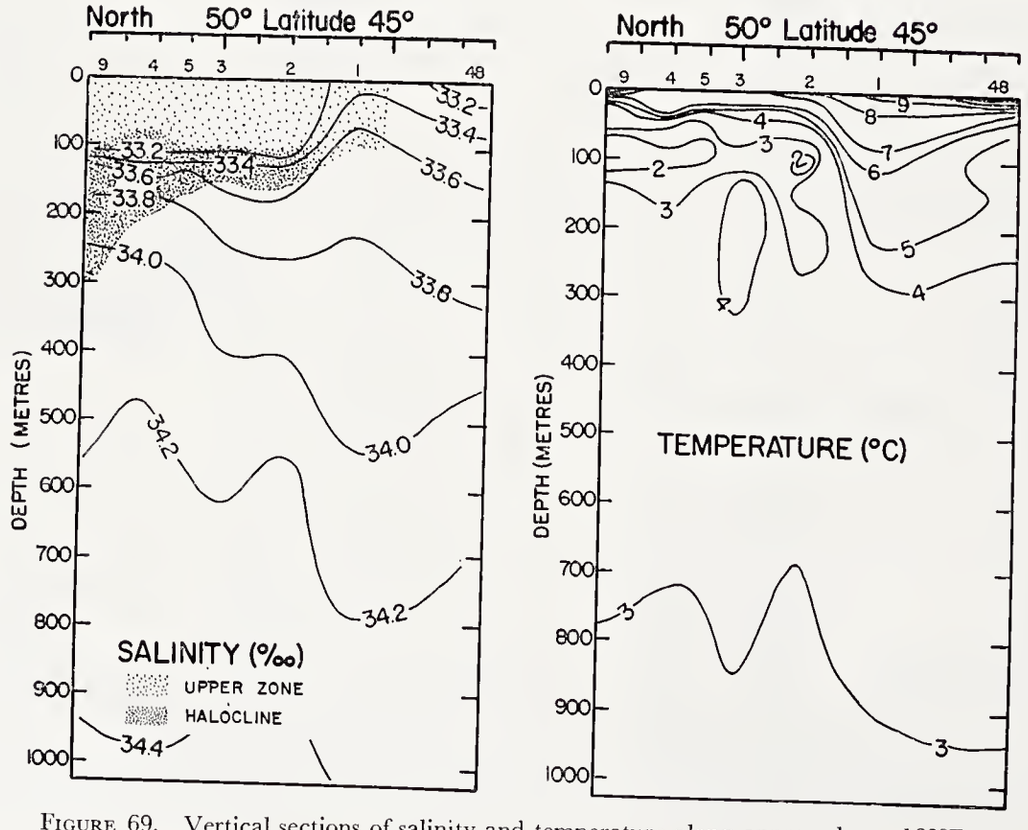


FIGURE 69. Vertical sections of salinity and temperature along approx. long. 165°E., summer 1957.

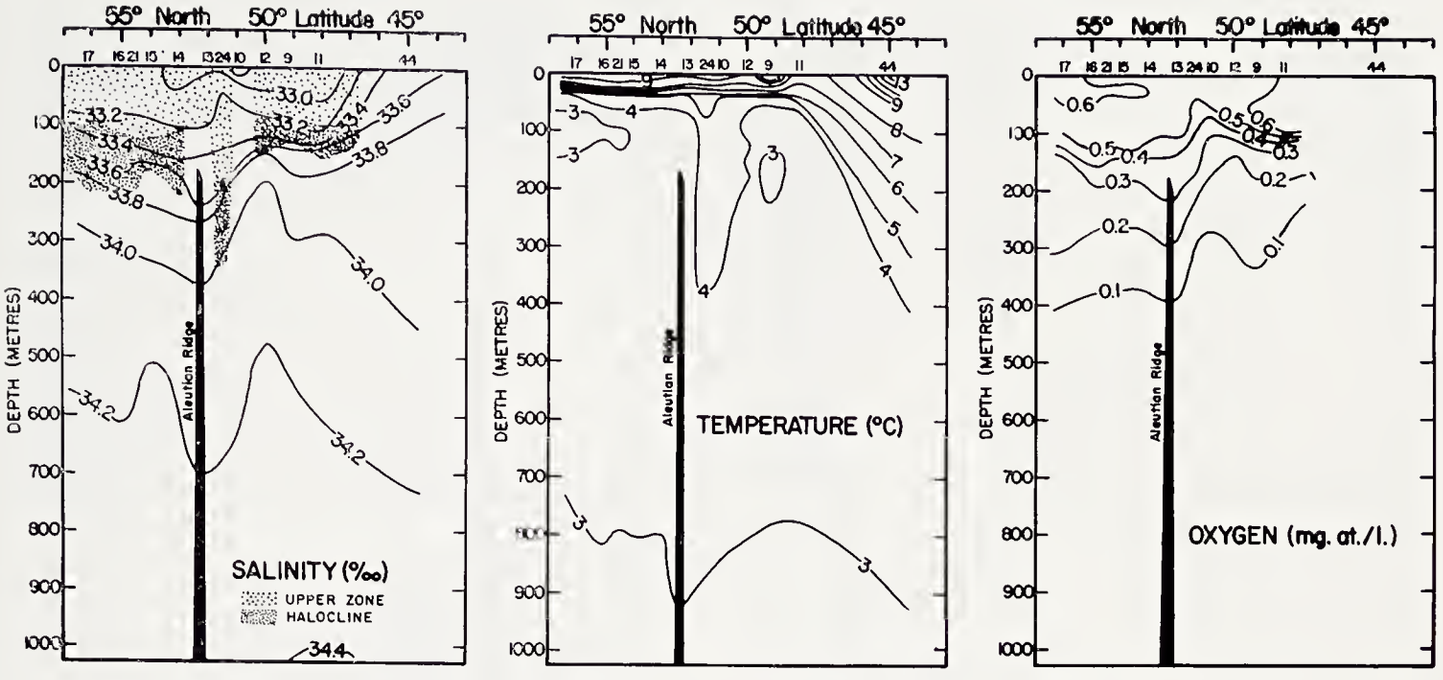


FIGURE 70. Vertical sections of salinity, temperature and dissolved oxygen along long. 175°E., summer 1957.

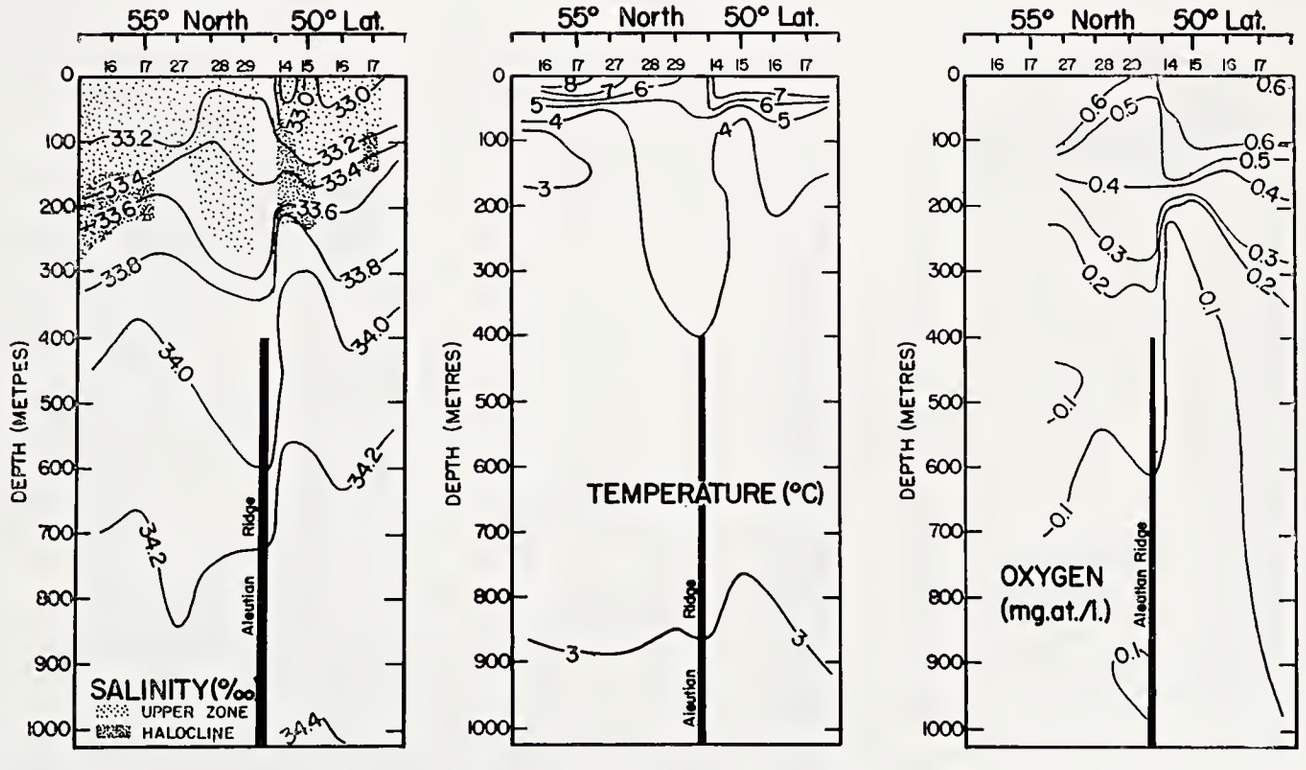


FIGURE 71. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 180°, summer 1957.

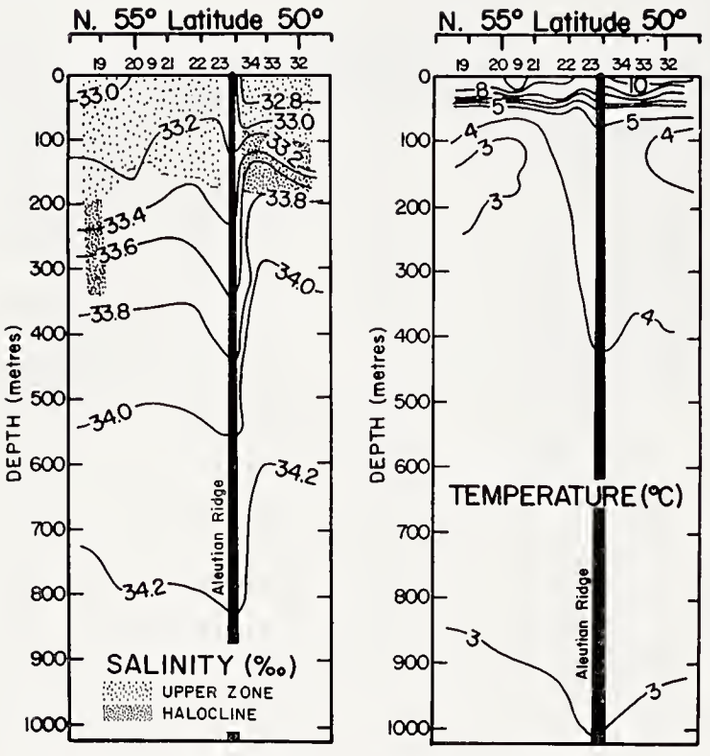


FIGURE 72. Vertical sections of salinity and temperature along long. 175°W., summer 1957.

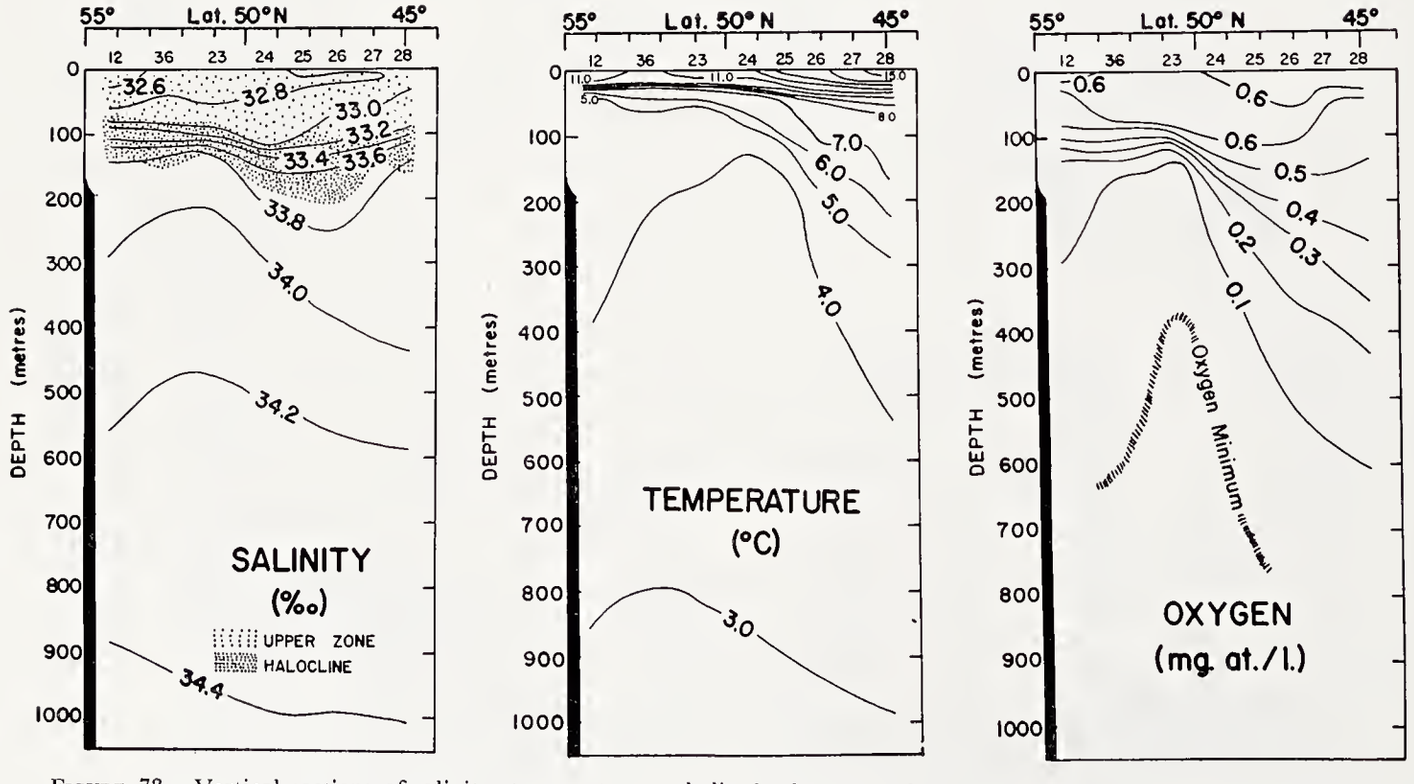


FIGURE 73. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 160°W., summer 1957.

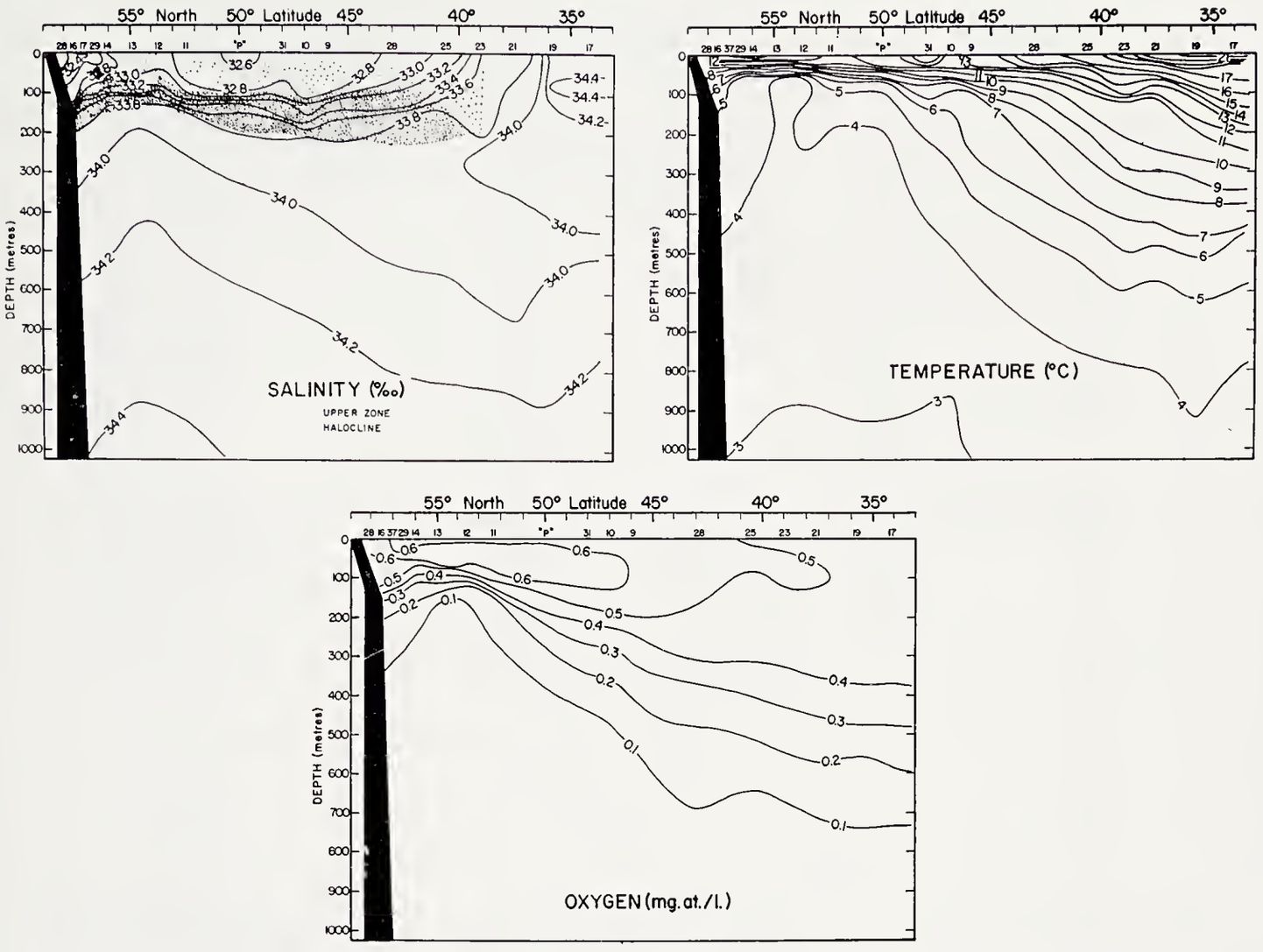


FIGURE 74. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 145°W., summer 1957.

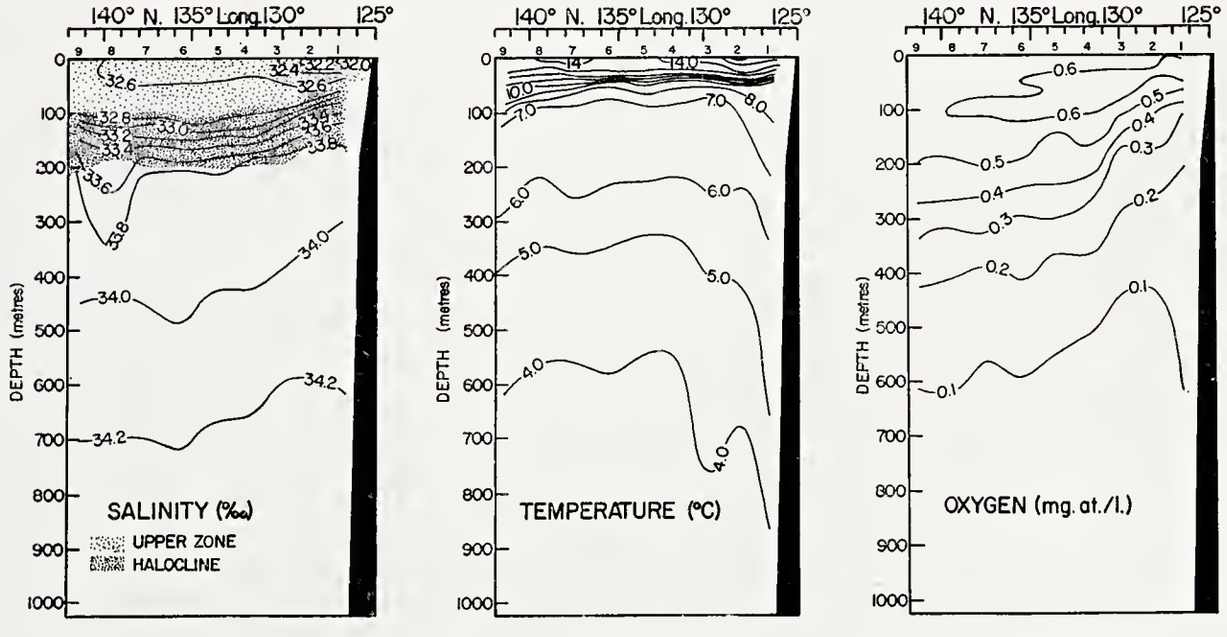


FIGURE 75. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 47°N., summer 1957.

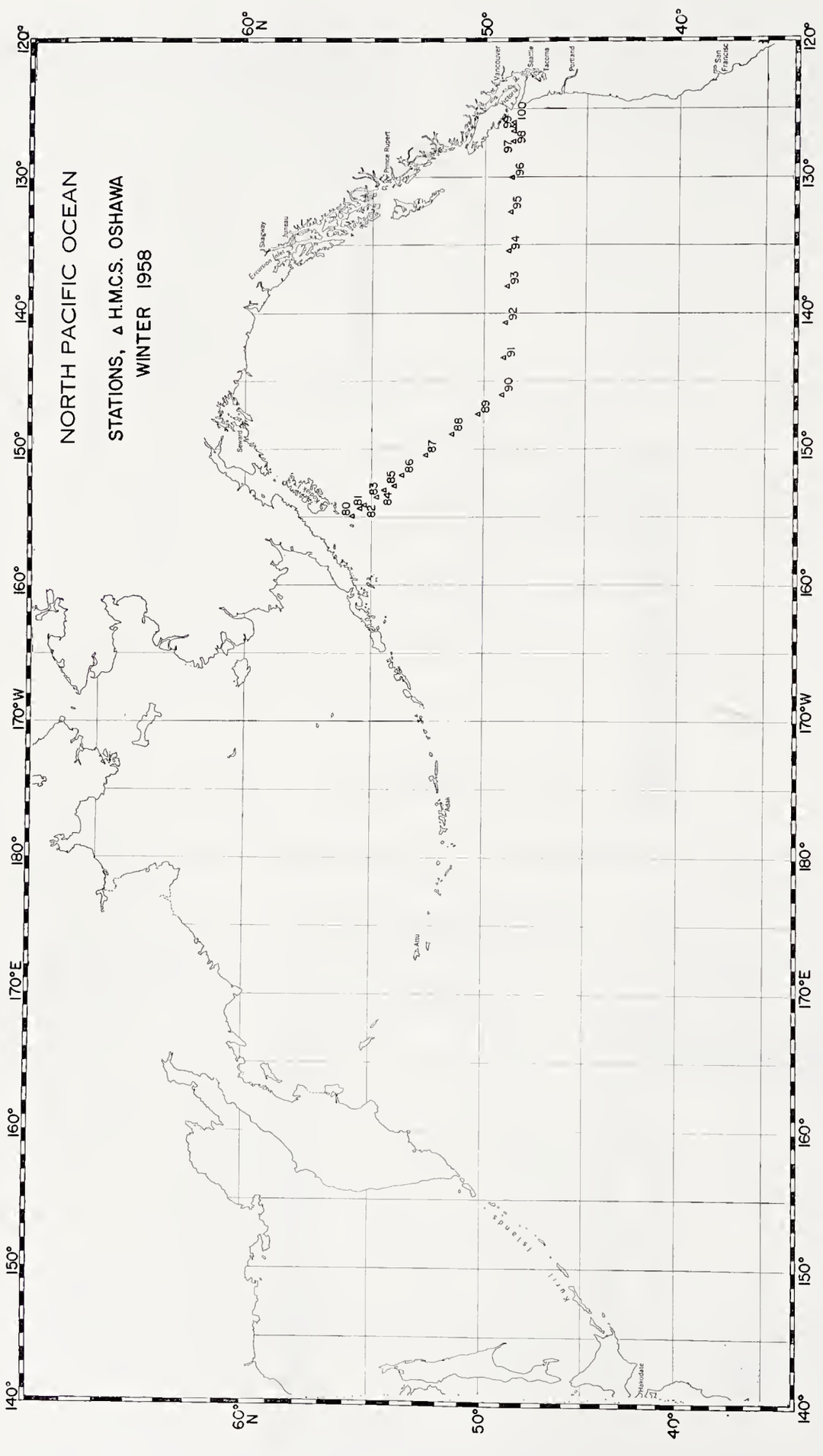


FIGURE 76. Locations of vertical sections, winter 1958.

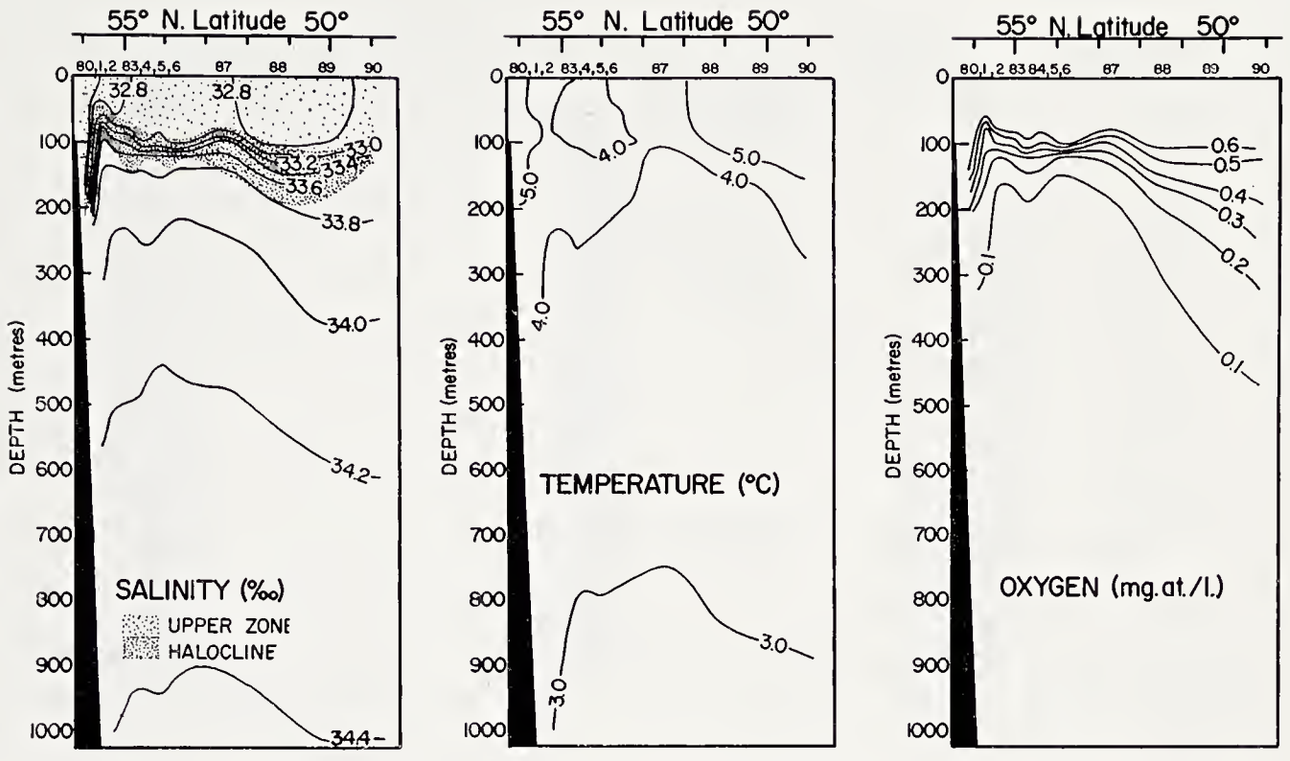


FIGURE 77. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 150°W., winter 1958.

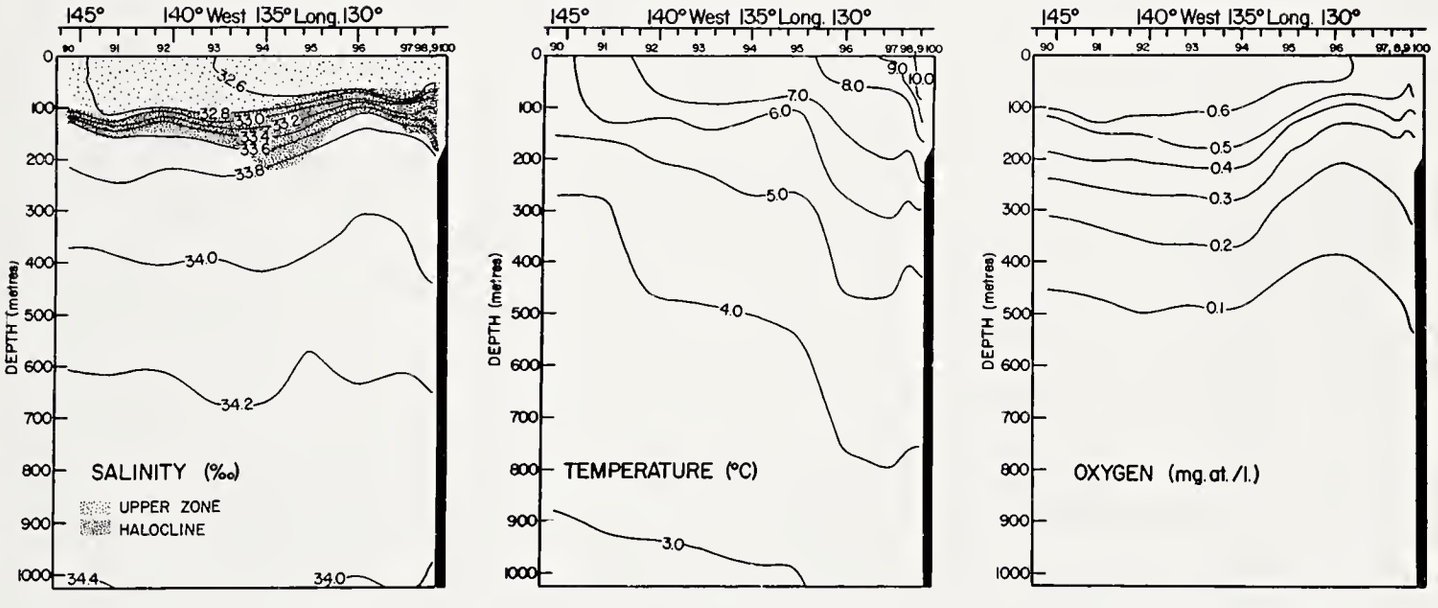


FIGURE 78. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 49°N., winter 1958.

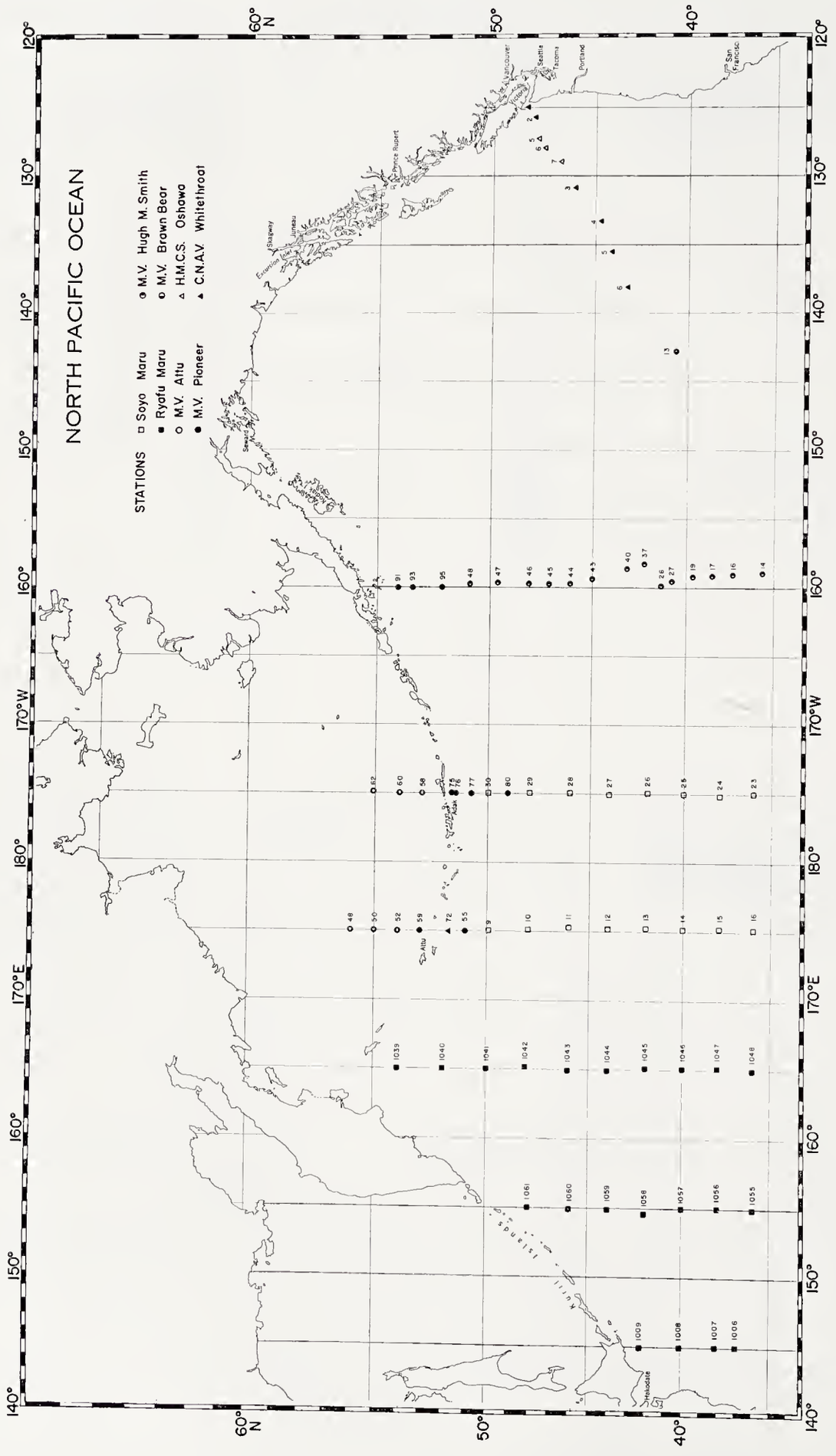


FIGURE 79. Locations of vertical sections, summer 1958.

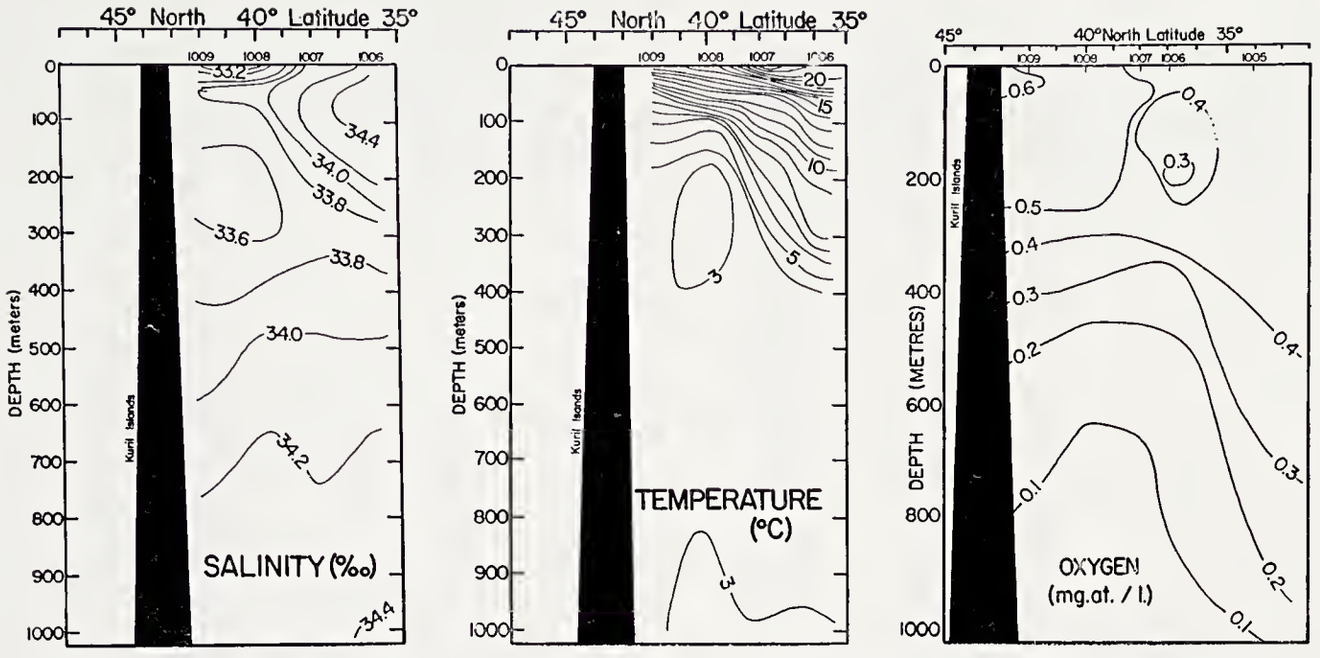


FIGURE 80. Vertical sections of salinity, temperature and dissolved oxygen along long. 145°E., summer 1958.

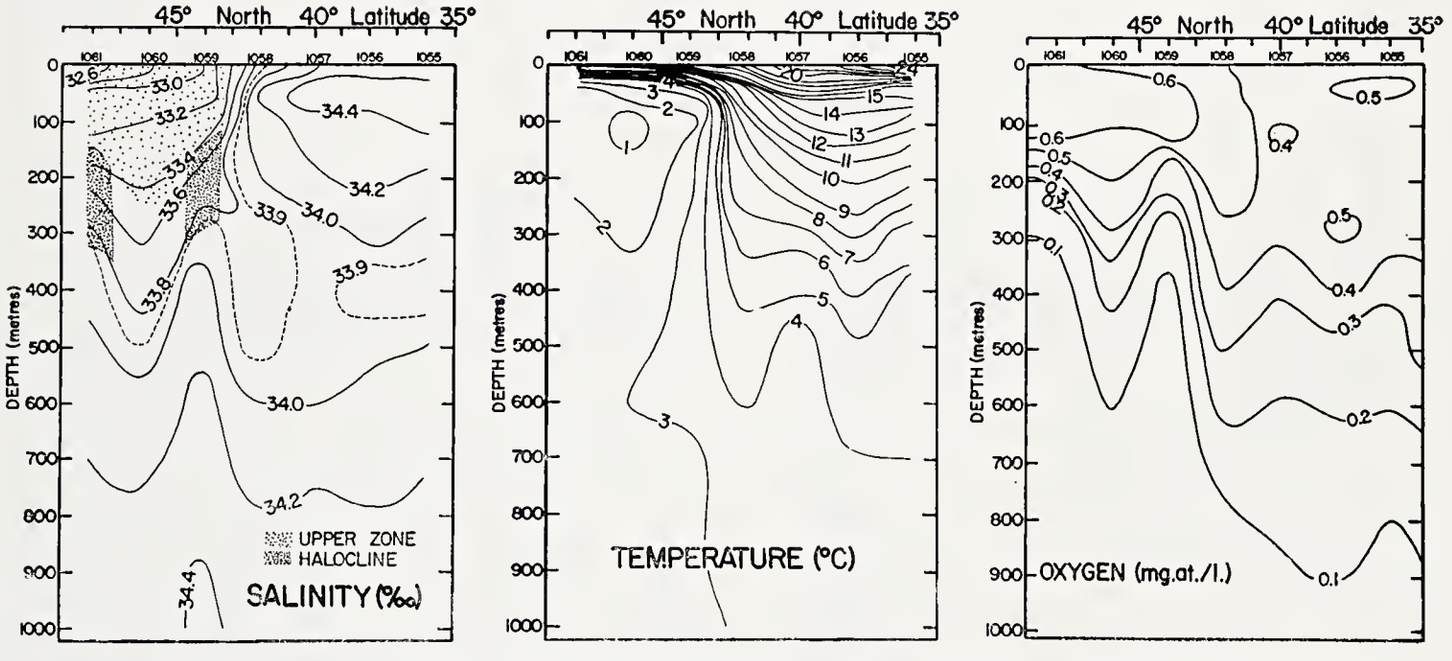


FIGURE 81. Vertical sections of salinity, temperature and dissolved oxygen along long. 155°E., summer 1958.

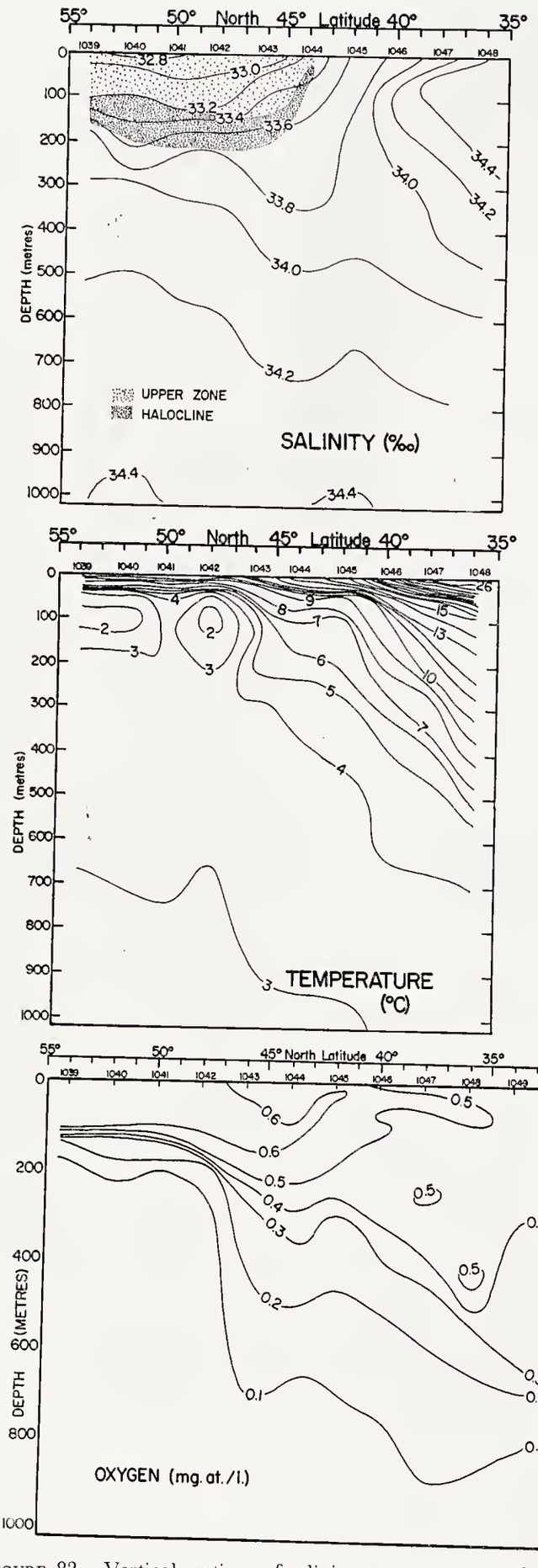


FIGURE 82. Vertical sections of salinity, temperature and dissolved oxygen along long. 165°E., summer 1958.

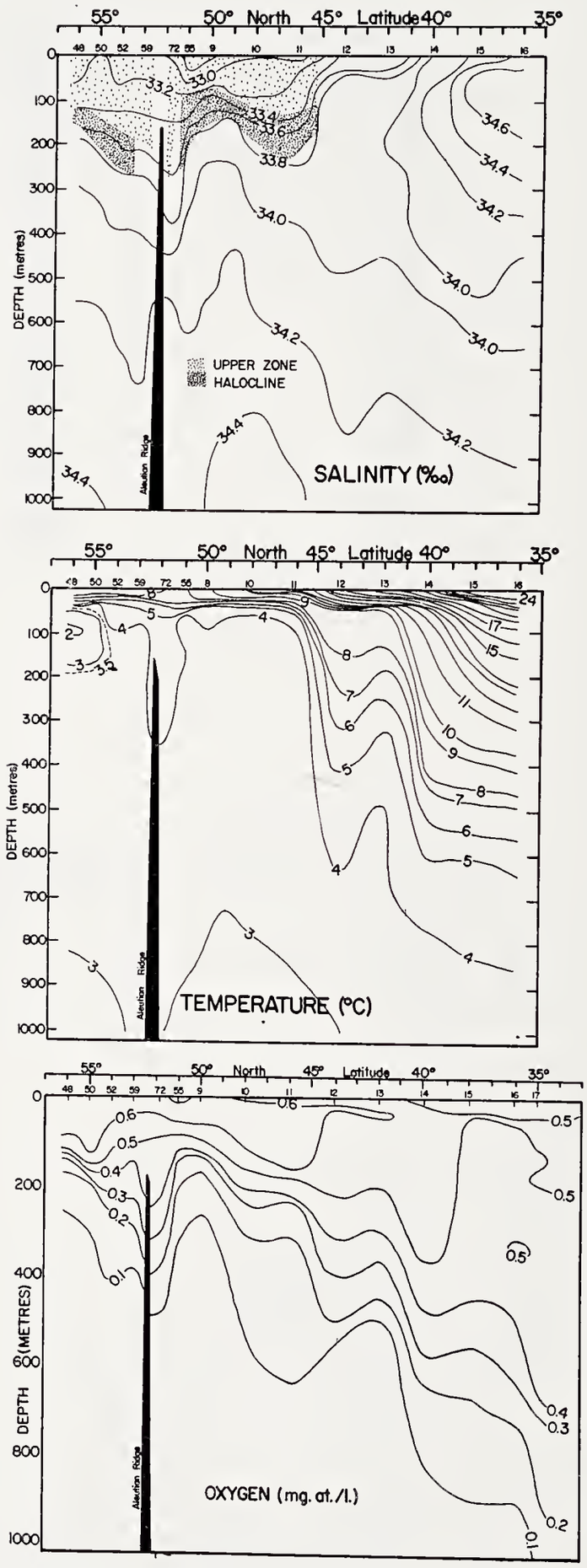


FIGURE 83. Vertical sections of salinity, temperature and dissolved oxygen along long. 175°E., summer 1958.

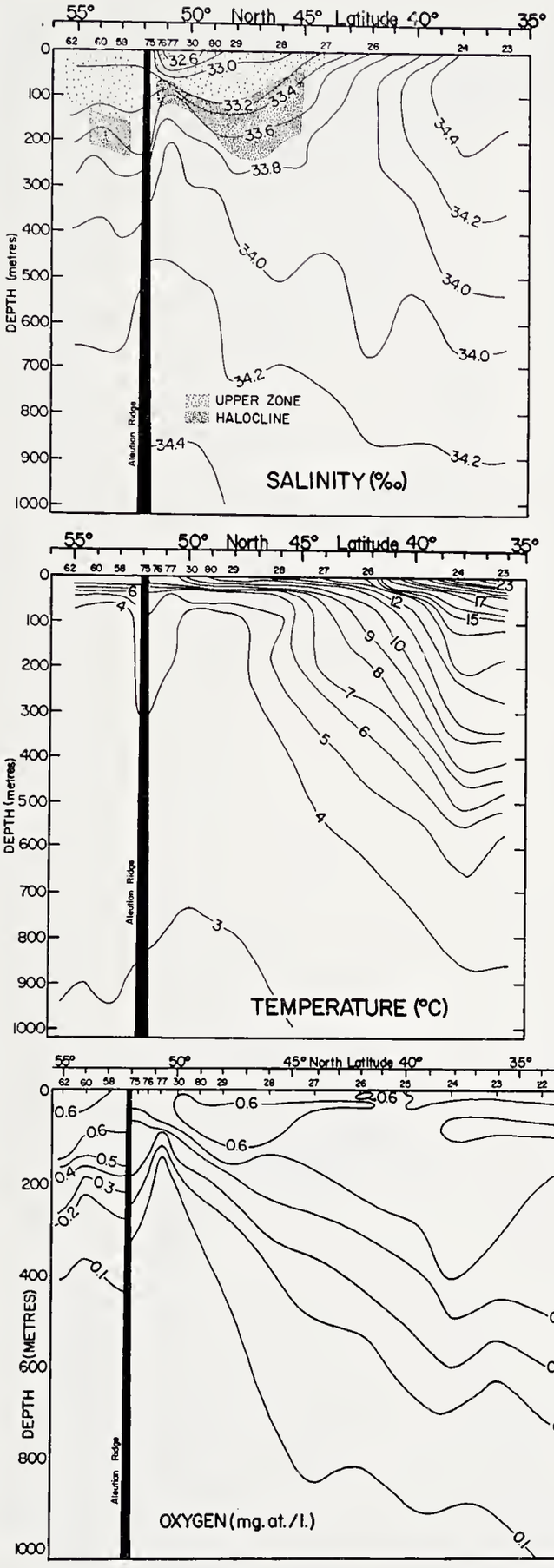


FIGURE 84. Vertical sections of salinity, temperature and dissolved oxygen along long. 175°W., summer 1958.

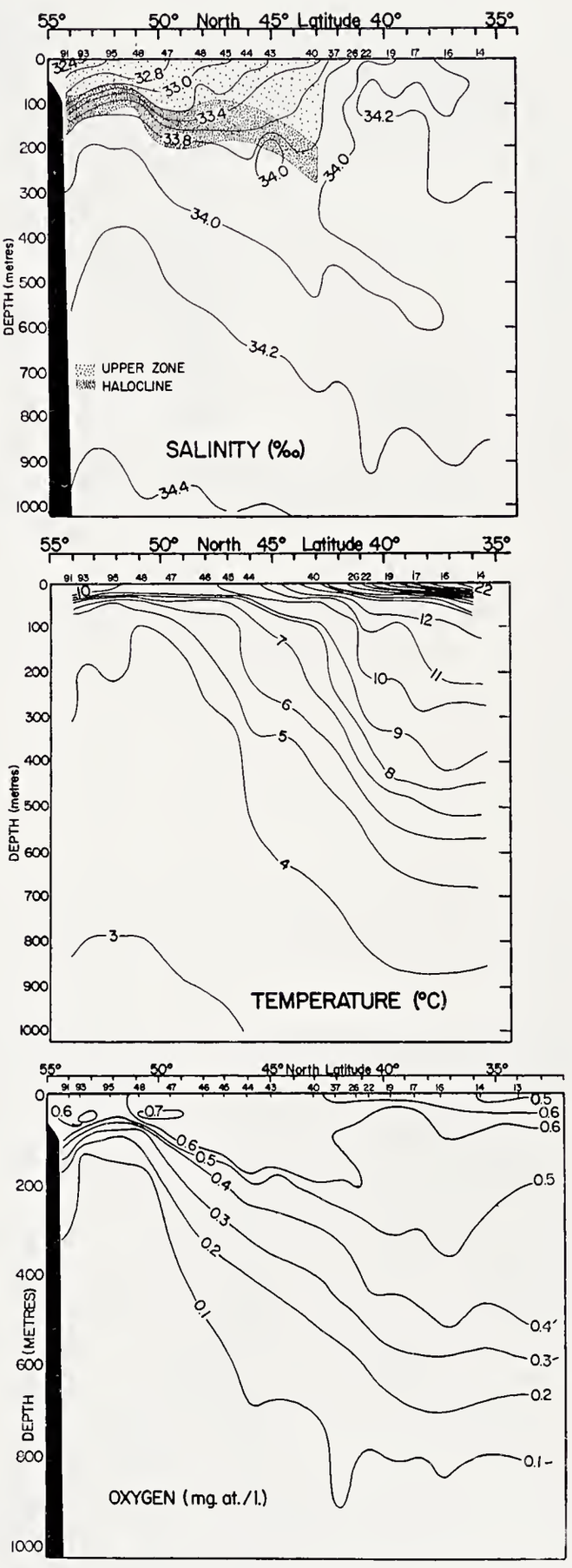


FIGURE 85. Vertical sections of salinity, temperature and dissolved oxygen along long. 160°W., summer 1958.

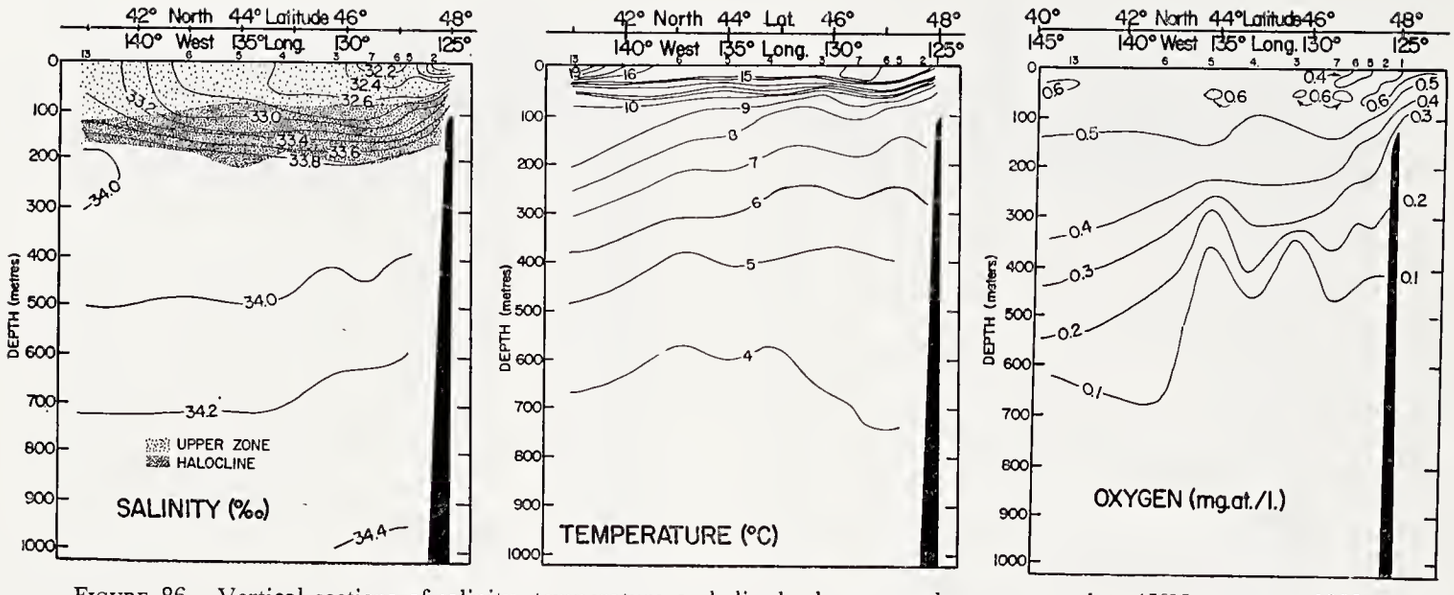


FIGURE 86. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 45°N., summer 1958.

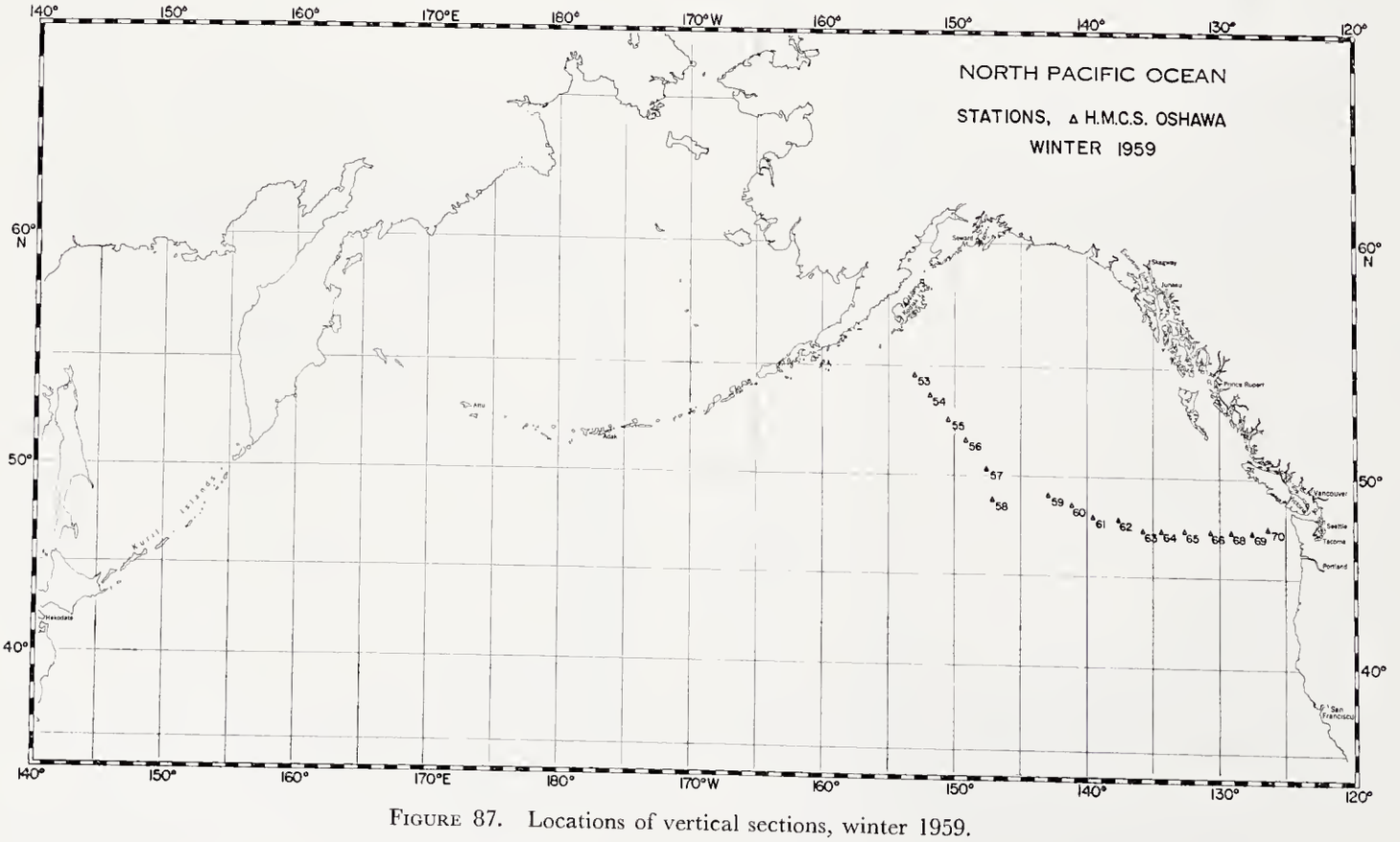


FIGURE 87. Locations of vertical sections, winter 1959.

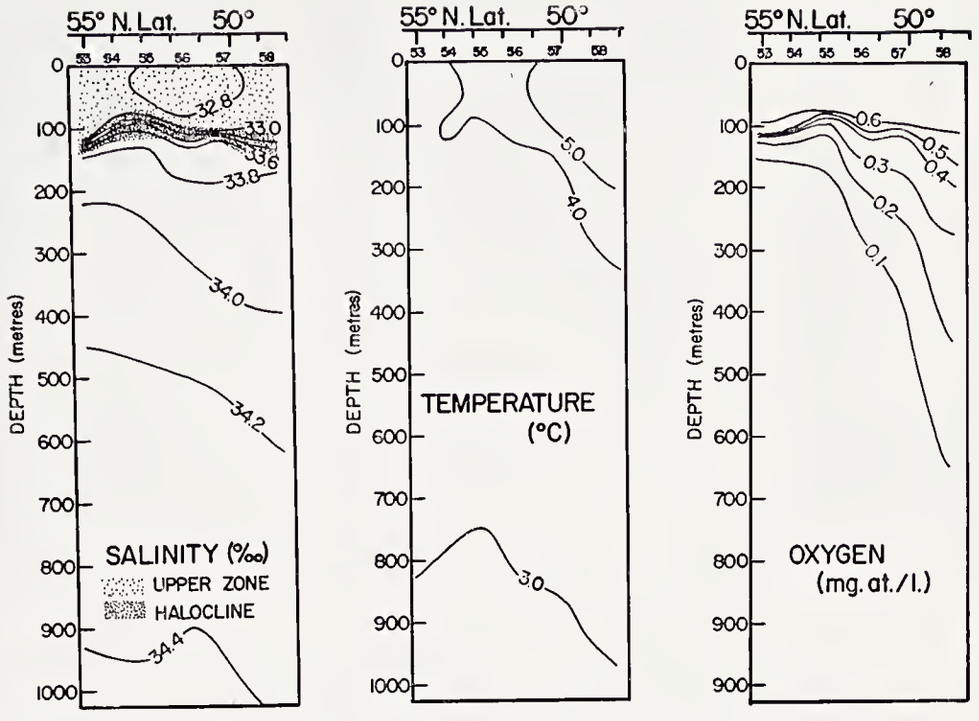


FIGURE 88. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 150°W., winter 1959.

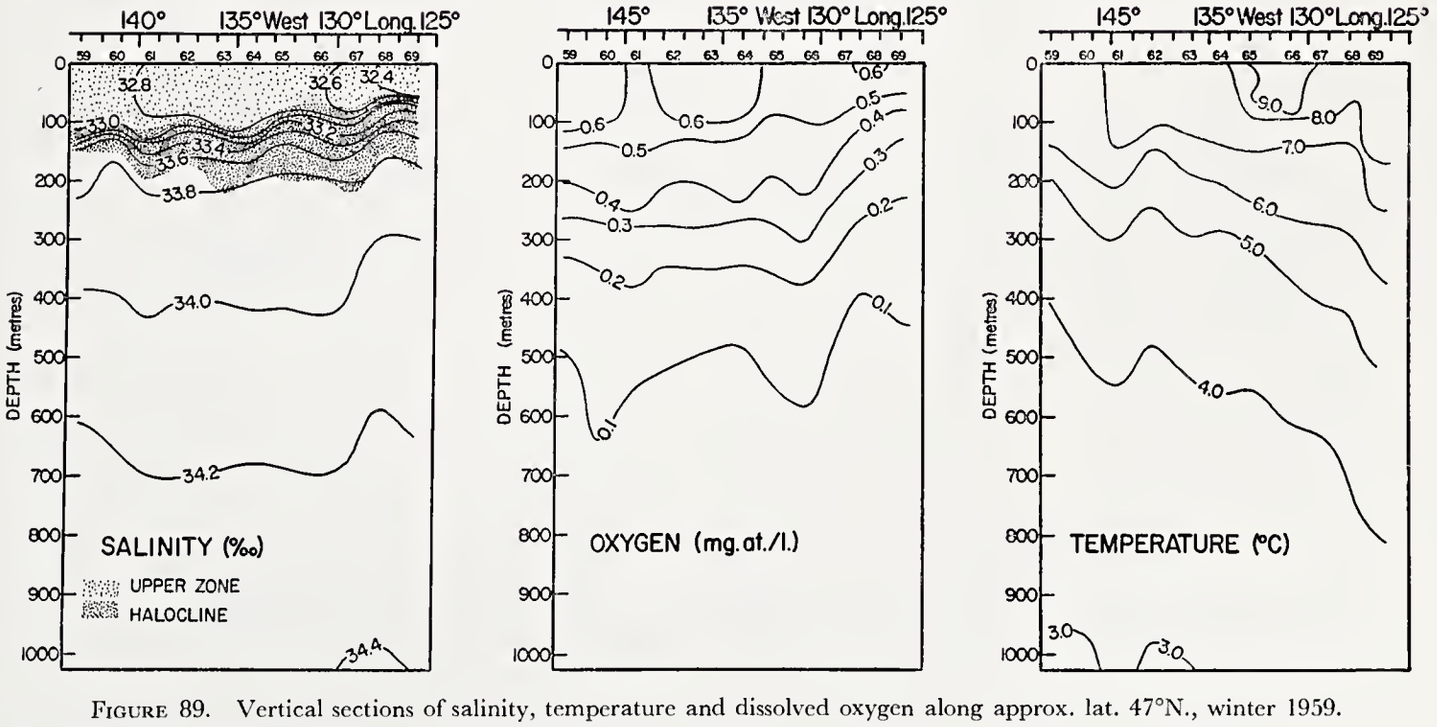


FIGURE 89. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 47°N., winter 1959.

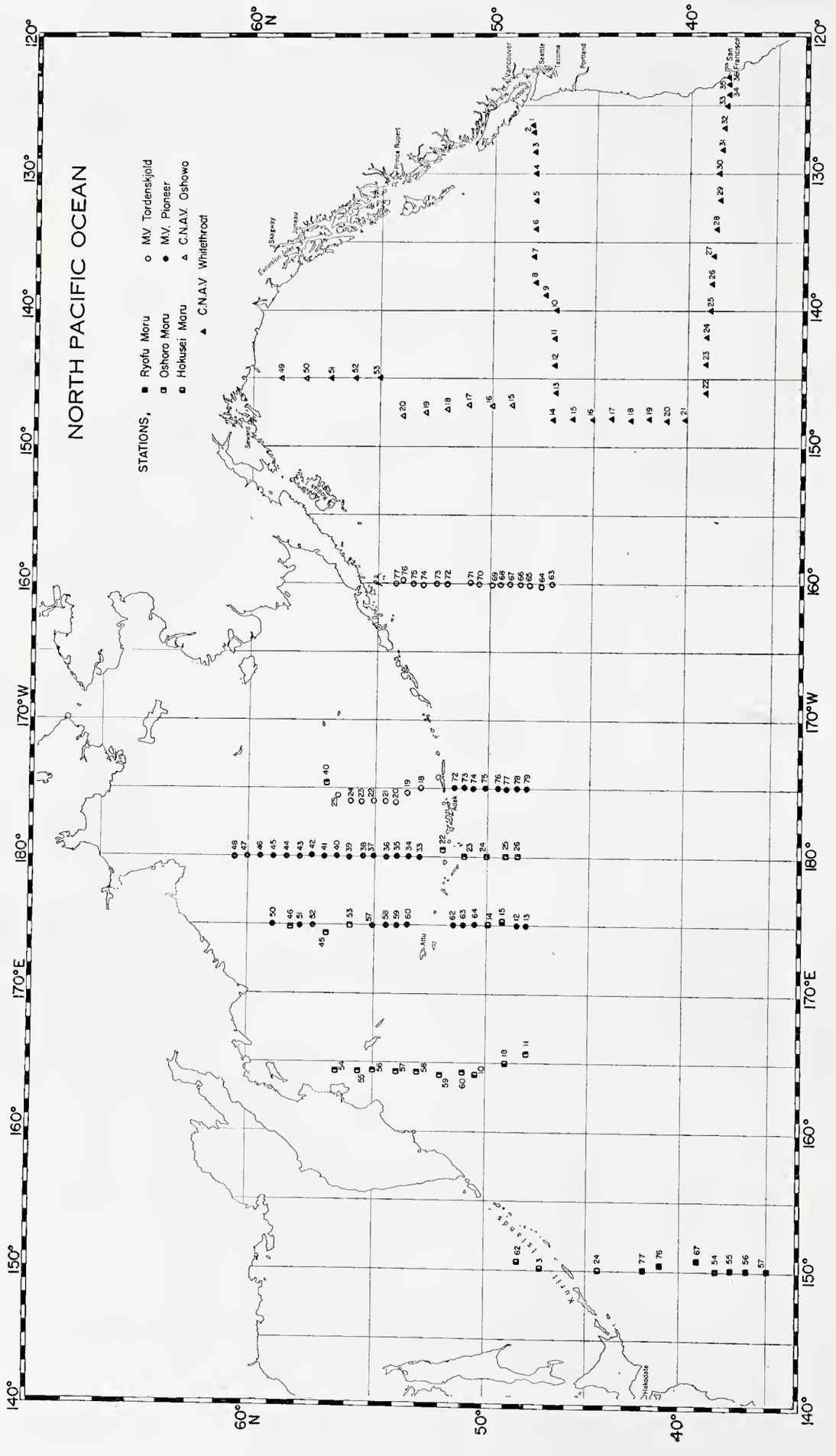


FIGURE 90. Locations of vertical sections, summer 1959.

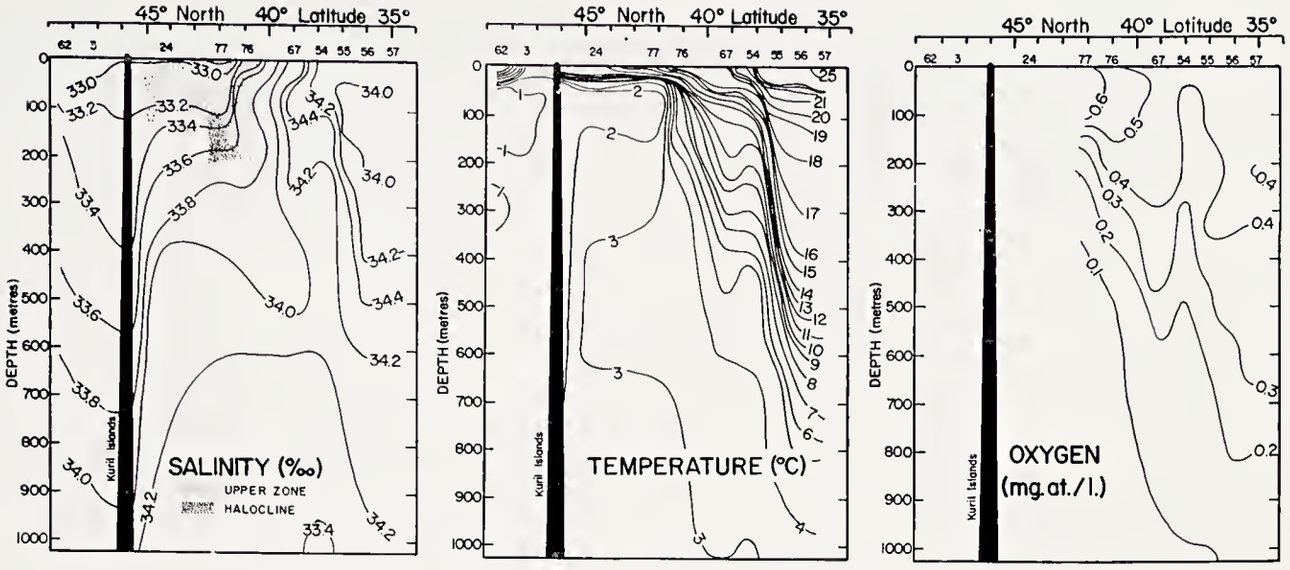


FIGURE 91. Vertical sections of salinity, temperature and dissolved oxygen along long. 150°E., summer 1959.

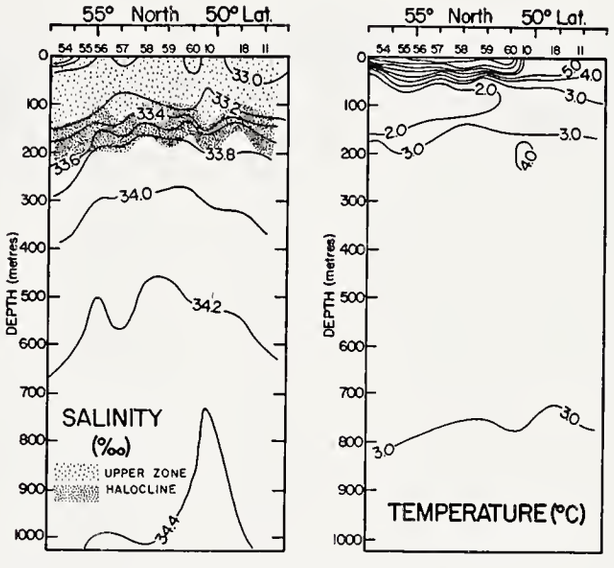


FIGURE 92. Vertical sections of salinity and temperature along approx. long. 165°E., summer 1959.

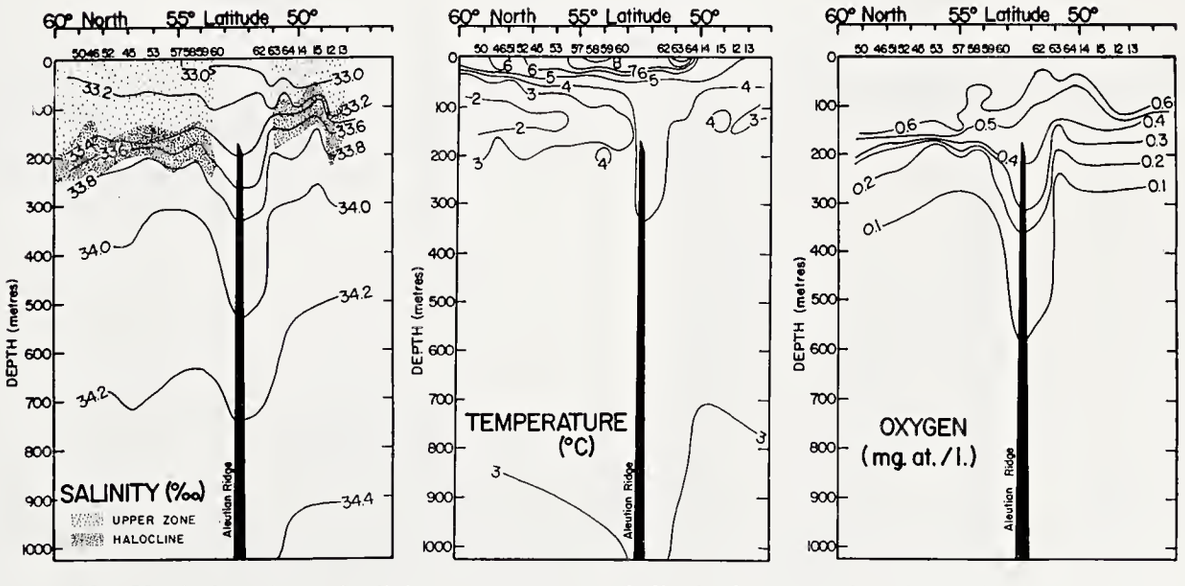


FIGURE 93. Vertical sections of salinity, temperature and dissolved oxygen along long. 175°E., summer 1959.

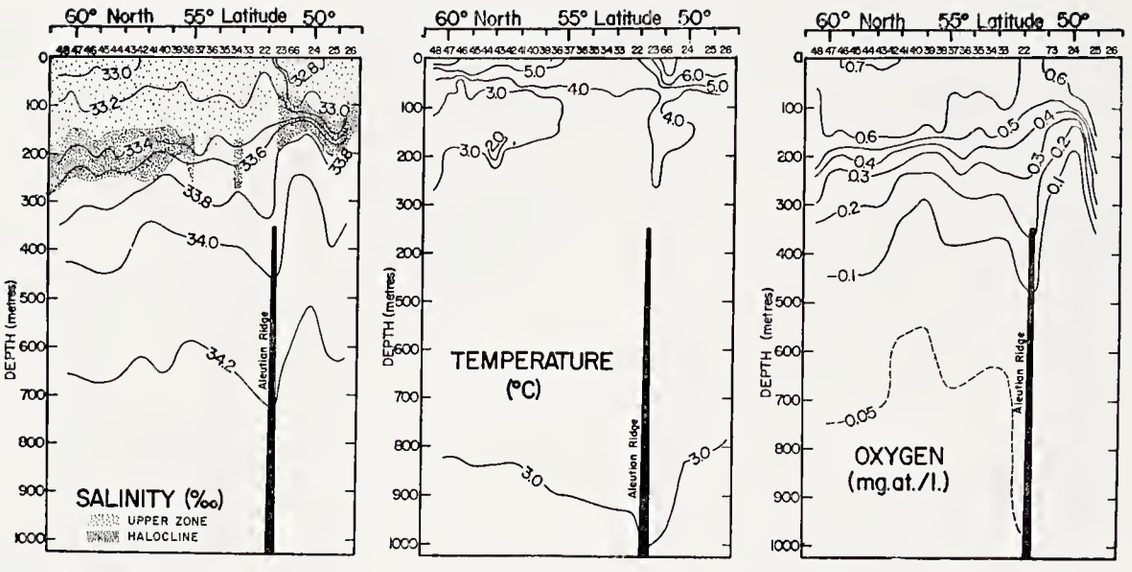


FIGURE 94. Vertical sections of salinity, temperature and dissolved oxygen along long. 180°, summer 1959.

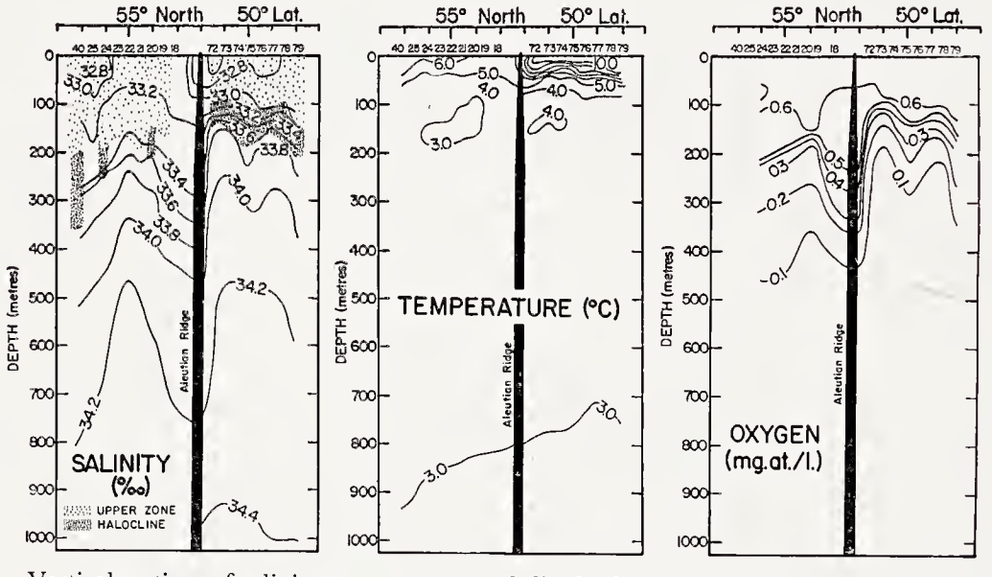


FIGURE 95. Vertical sections of salinity, temperature and dissolved oxygen along long. 175°W., summer 1959.

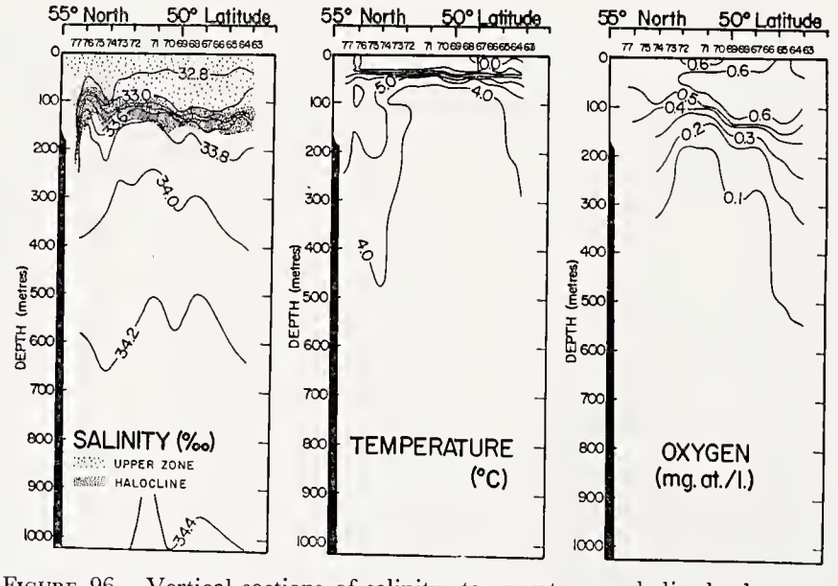


FIGURE 96. Vertical sections of salinity, temperature and dissolved oxygen along long. 160°W., summer 1959.

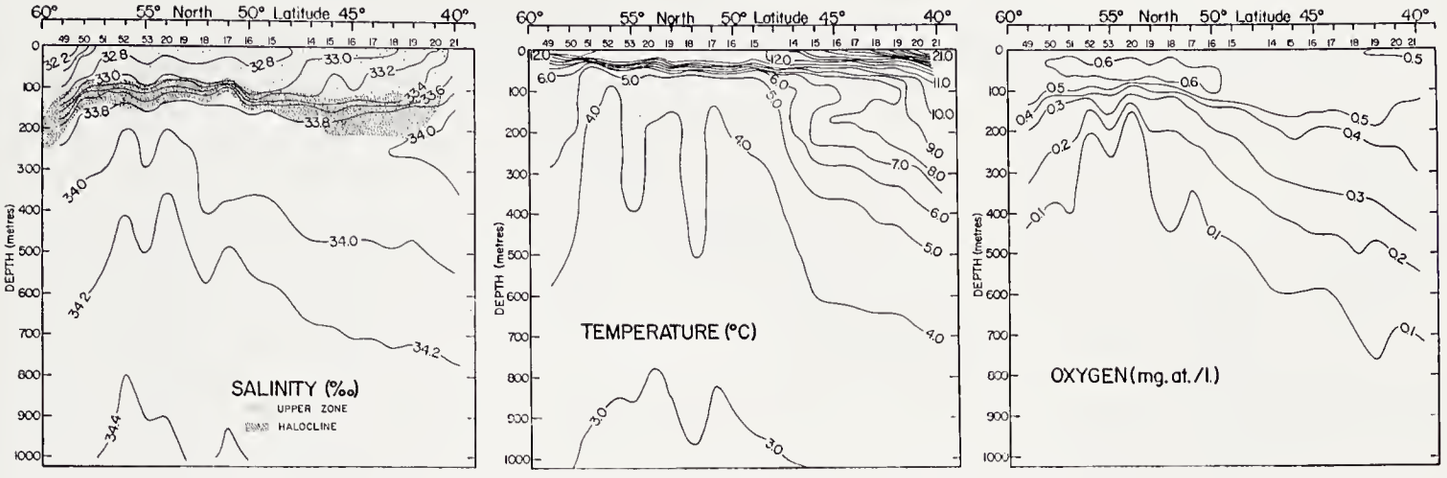


FIGURE 97. Vertical sections of salinity, temperature and dissolved oxygen along approx. long. 145°W., summer 1959.

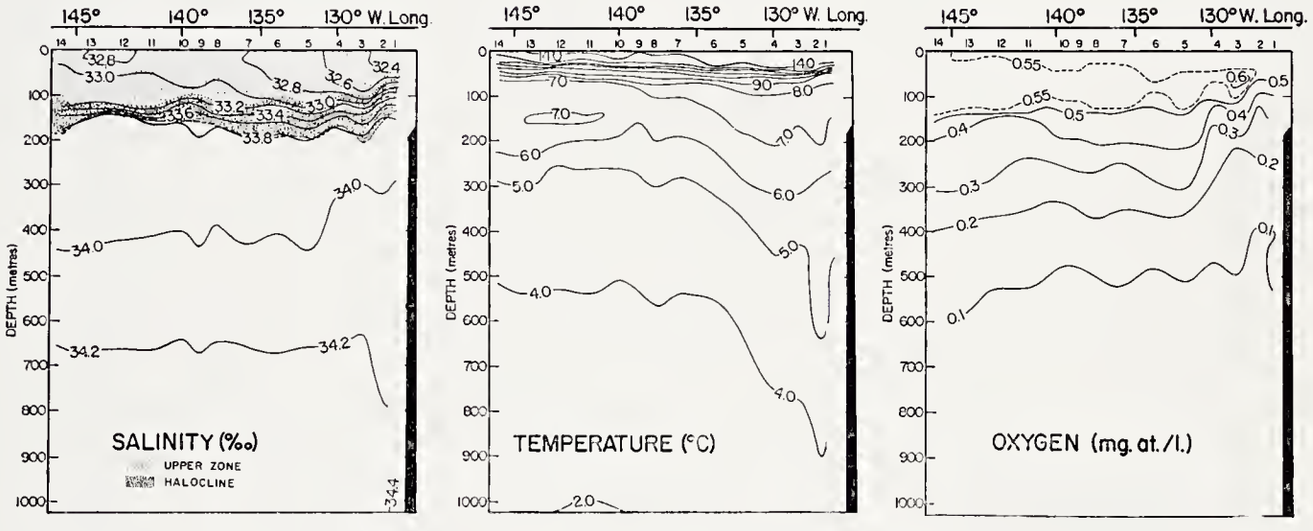


FIGURE 98. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 48°N., summer 1959.

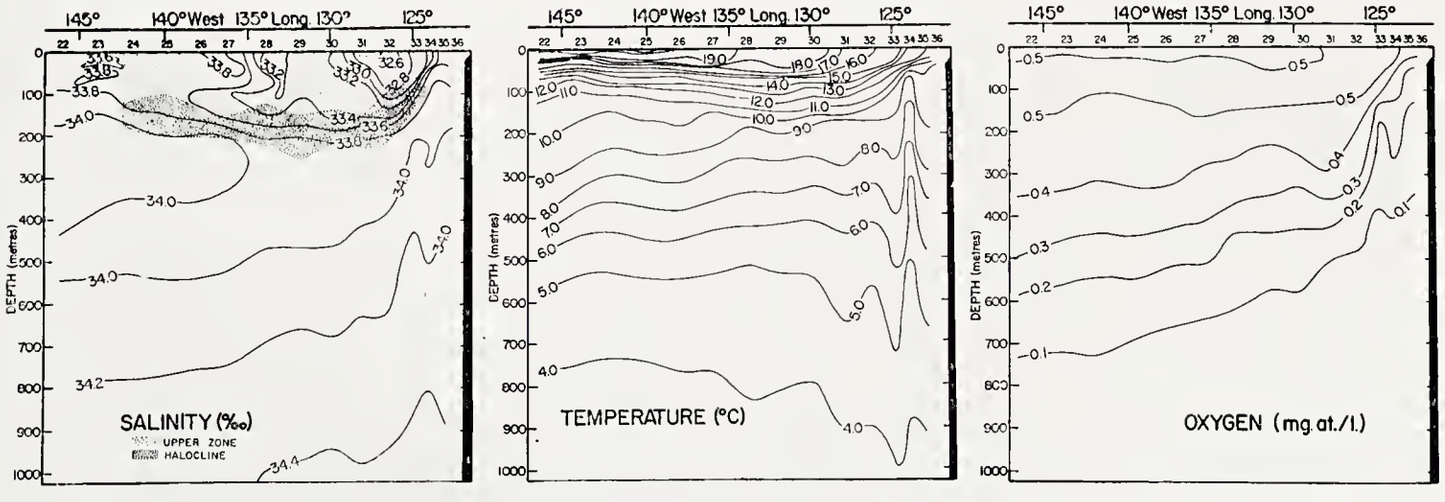
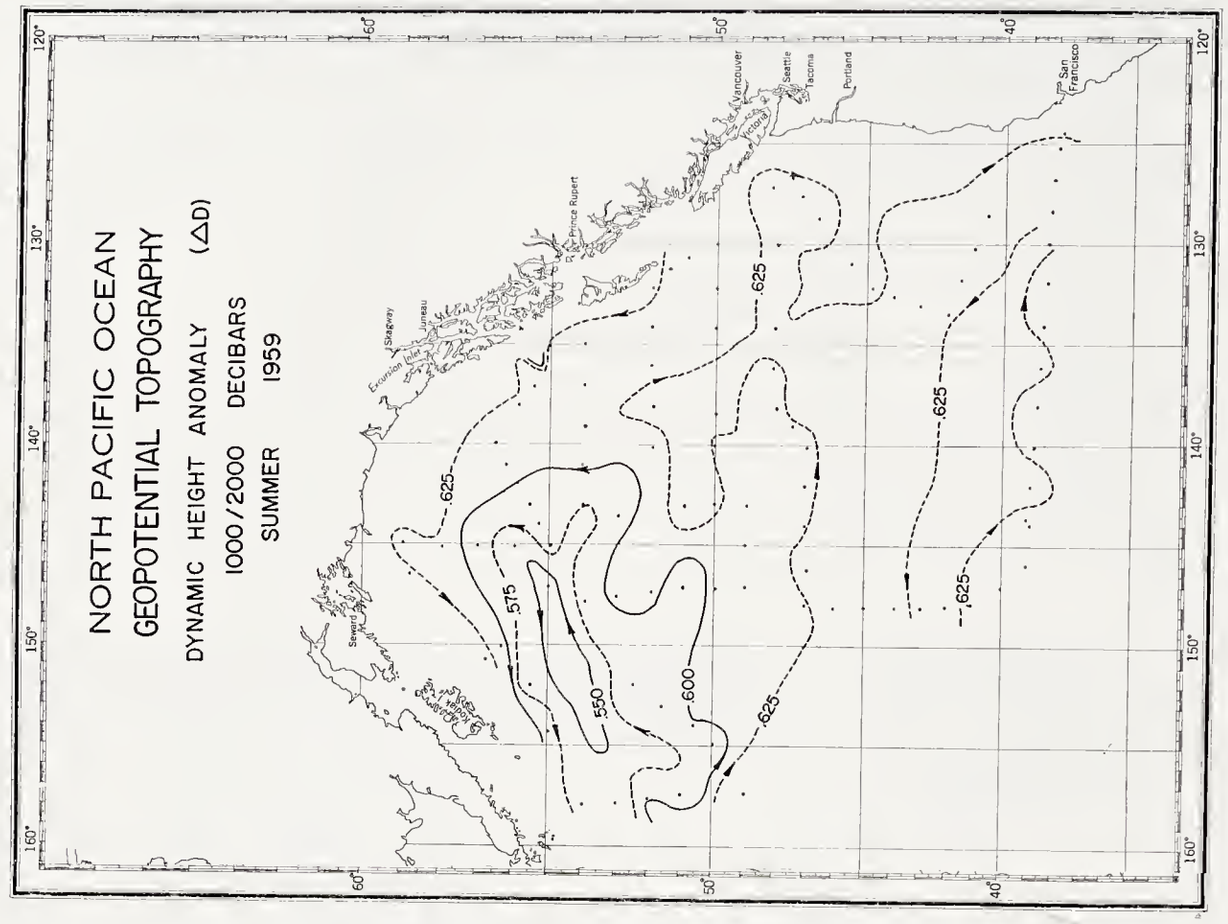


FIGURE 99. Vertical sections of salinity, temperature and dissolved oxygen along approx. lat. 38°N., summer 1959.



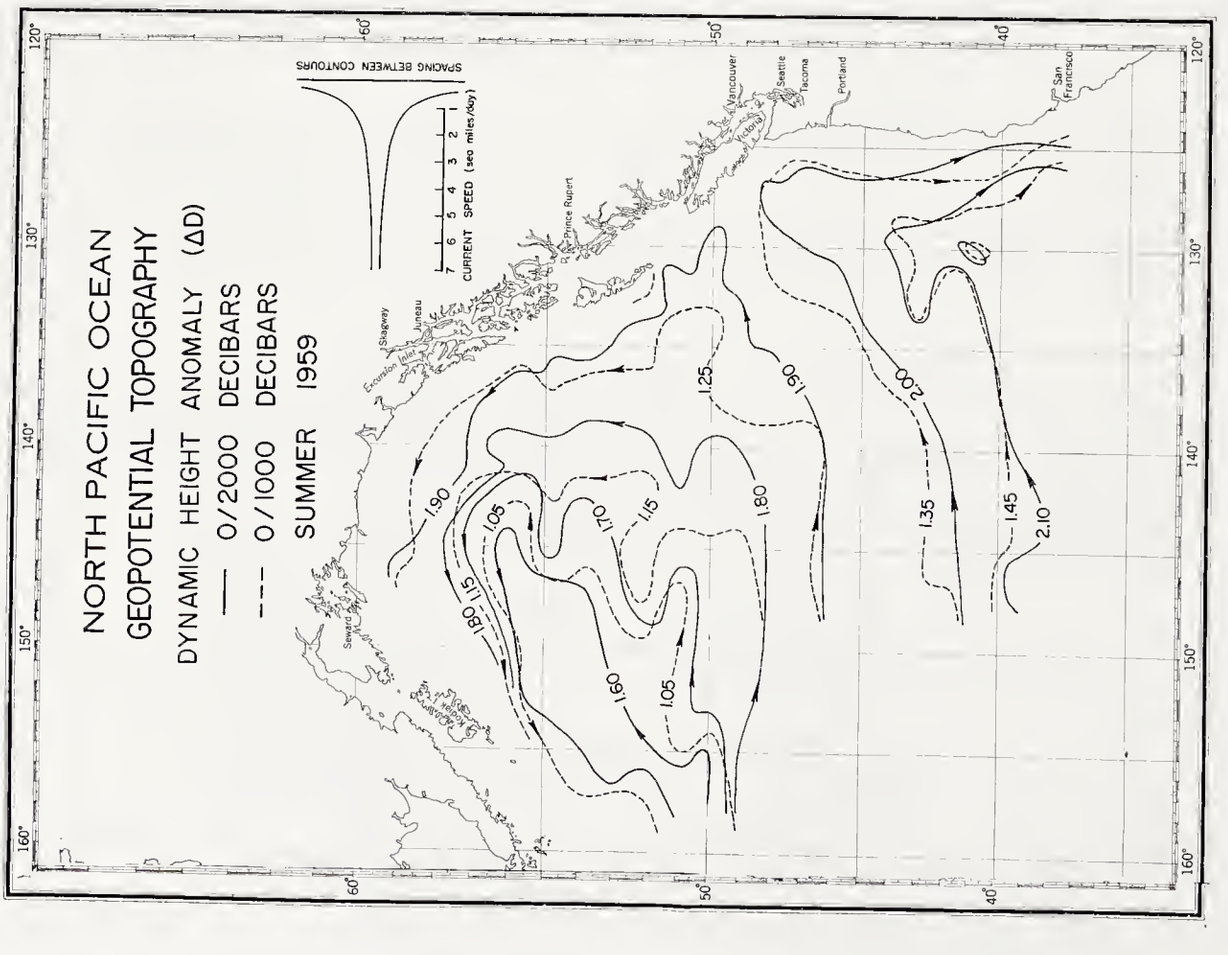


FIGURE 100. Geopotential topography, 0/1000, 0/2000 and 1000/2000 decibars, summer 1959.

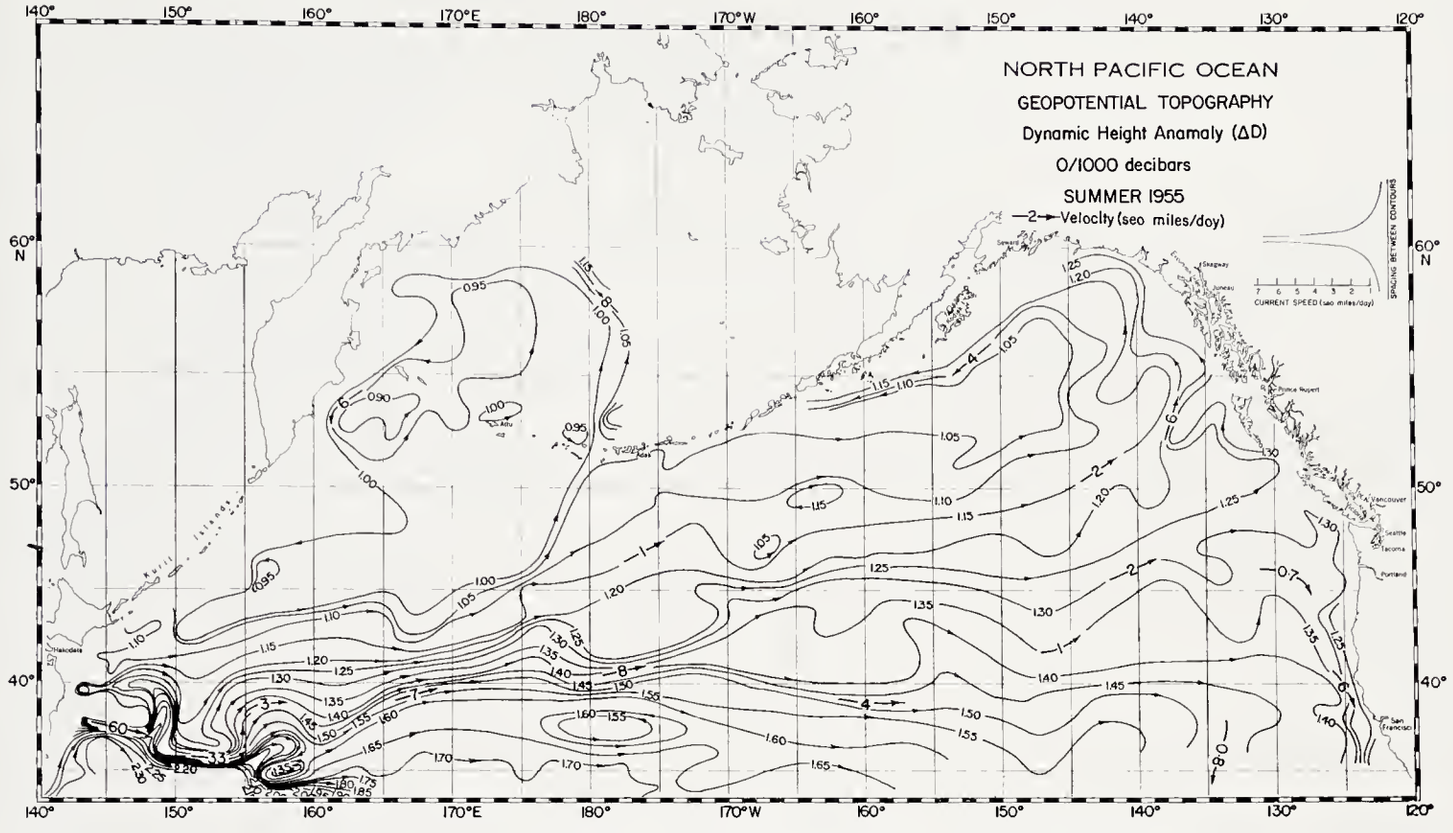


FIGURE 101. Geopotential topography, 0/1000 decibars, summer 1955.

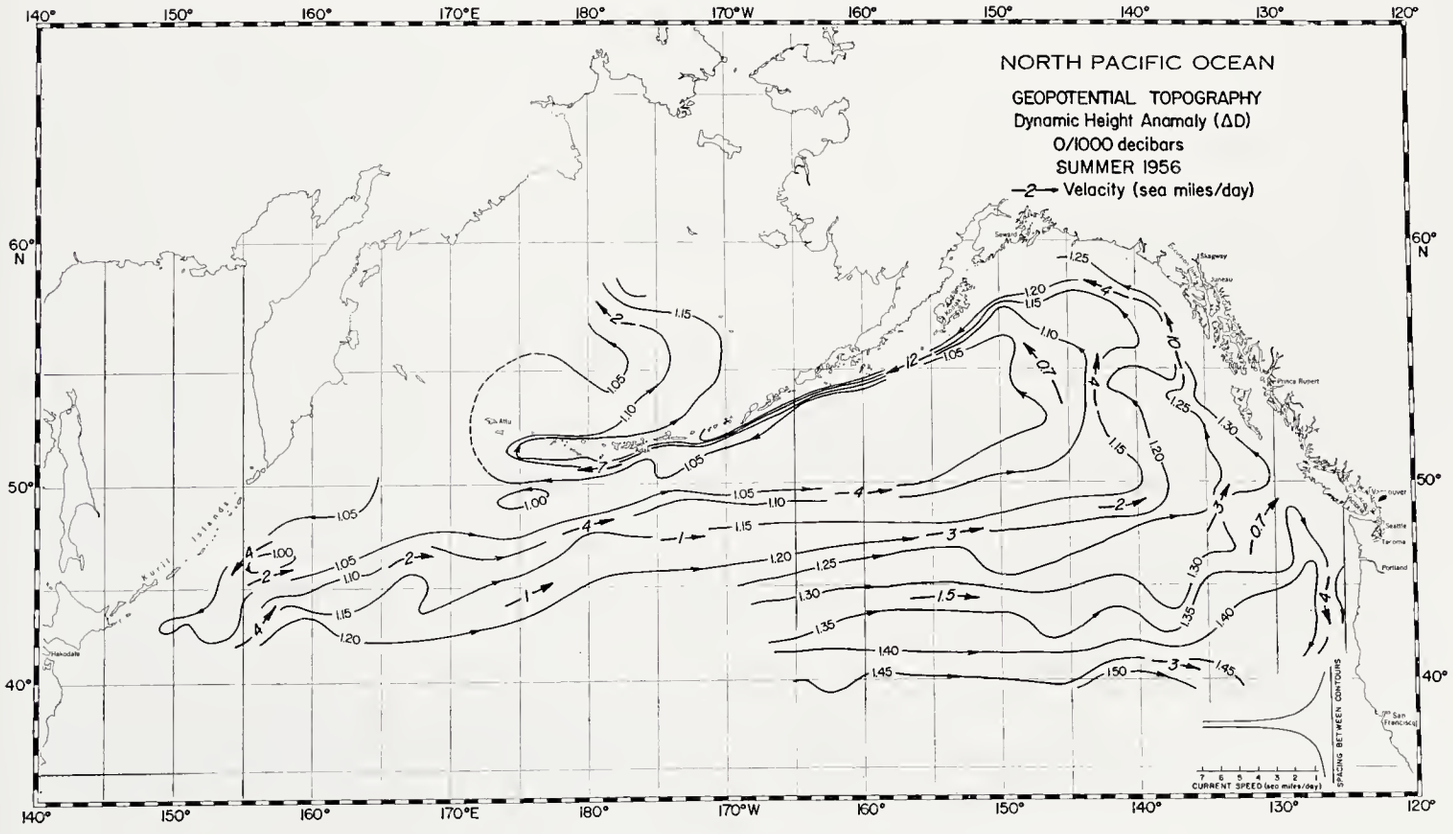


FIGURE 102. Geopotential topography, 0/1000 decibars, summer 1956.

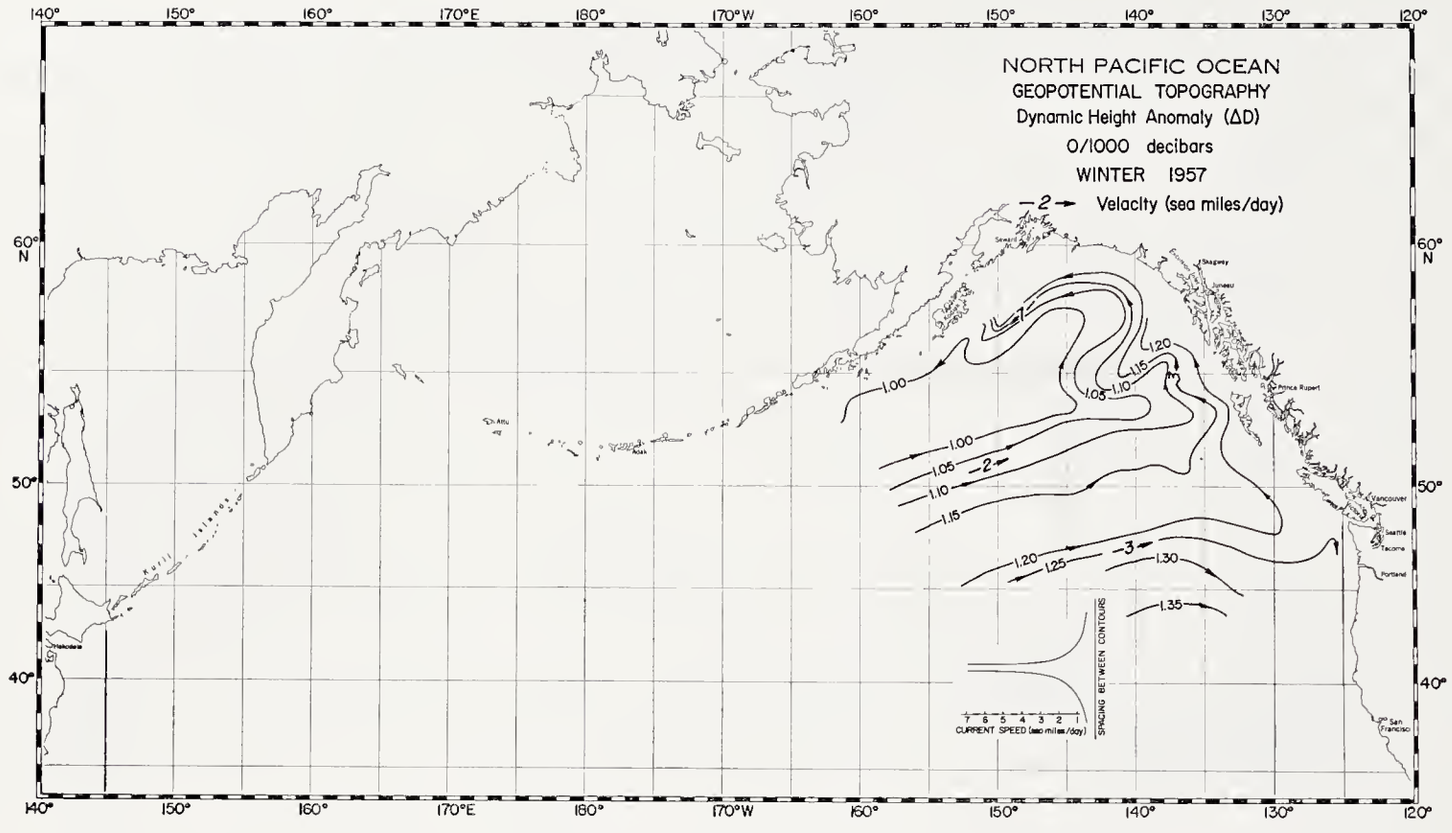


FIGURE 103. Geopotential topography, 0/1000 decibars, winter 1957.

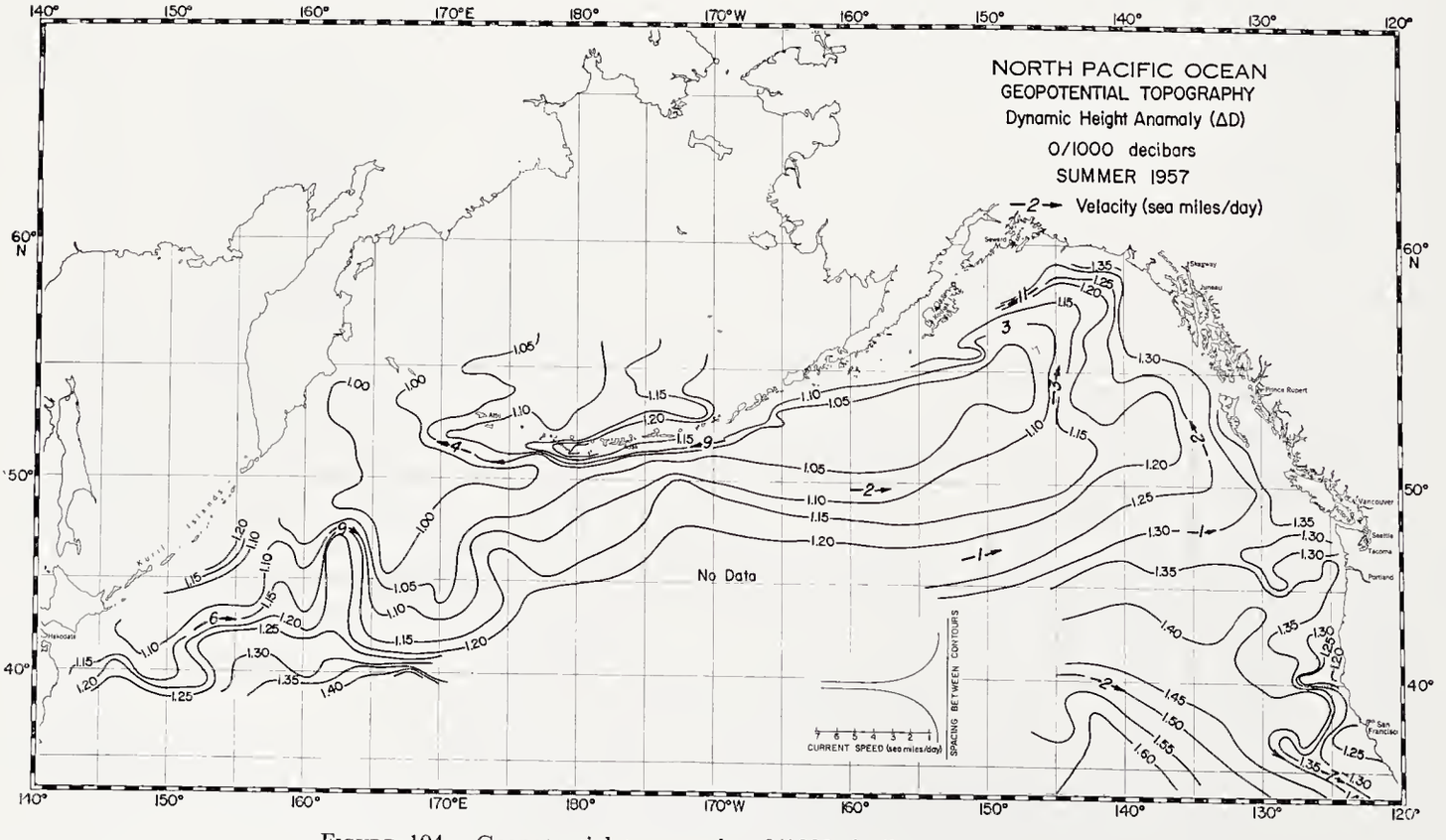


FIGURE 104. Geopotential topography, 0/1000 decibars, summer 1957.

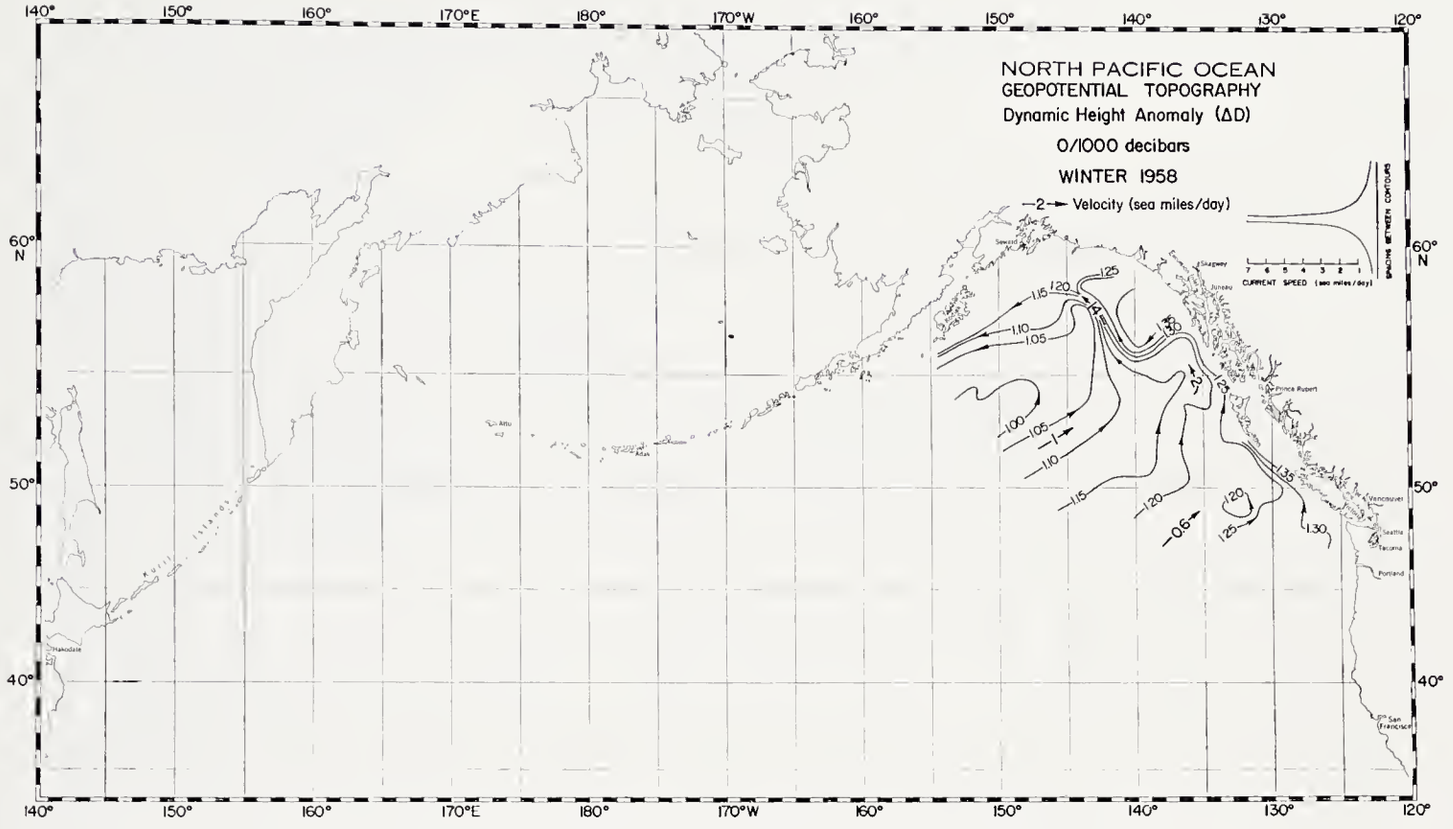


FIGURE 105. Geopotential topography, 0/1000 decibars, winter 1958.

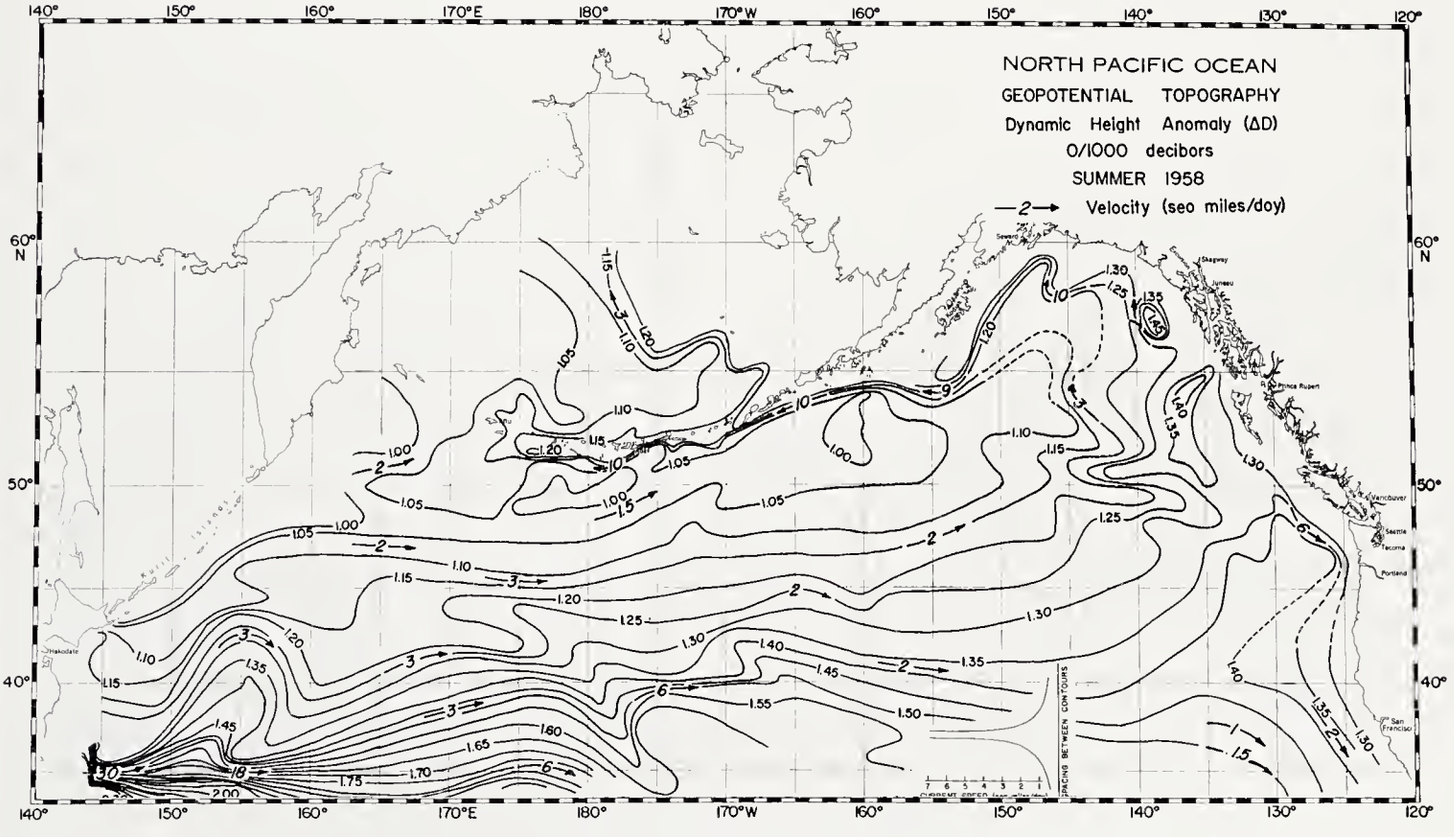


FIGURE 106. Geopotential topography, 0/1000 decibars, summer 1958.

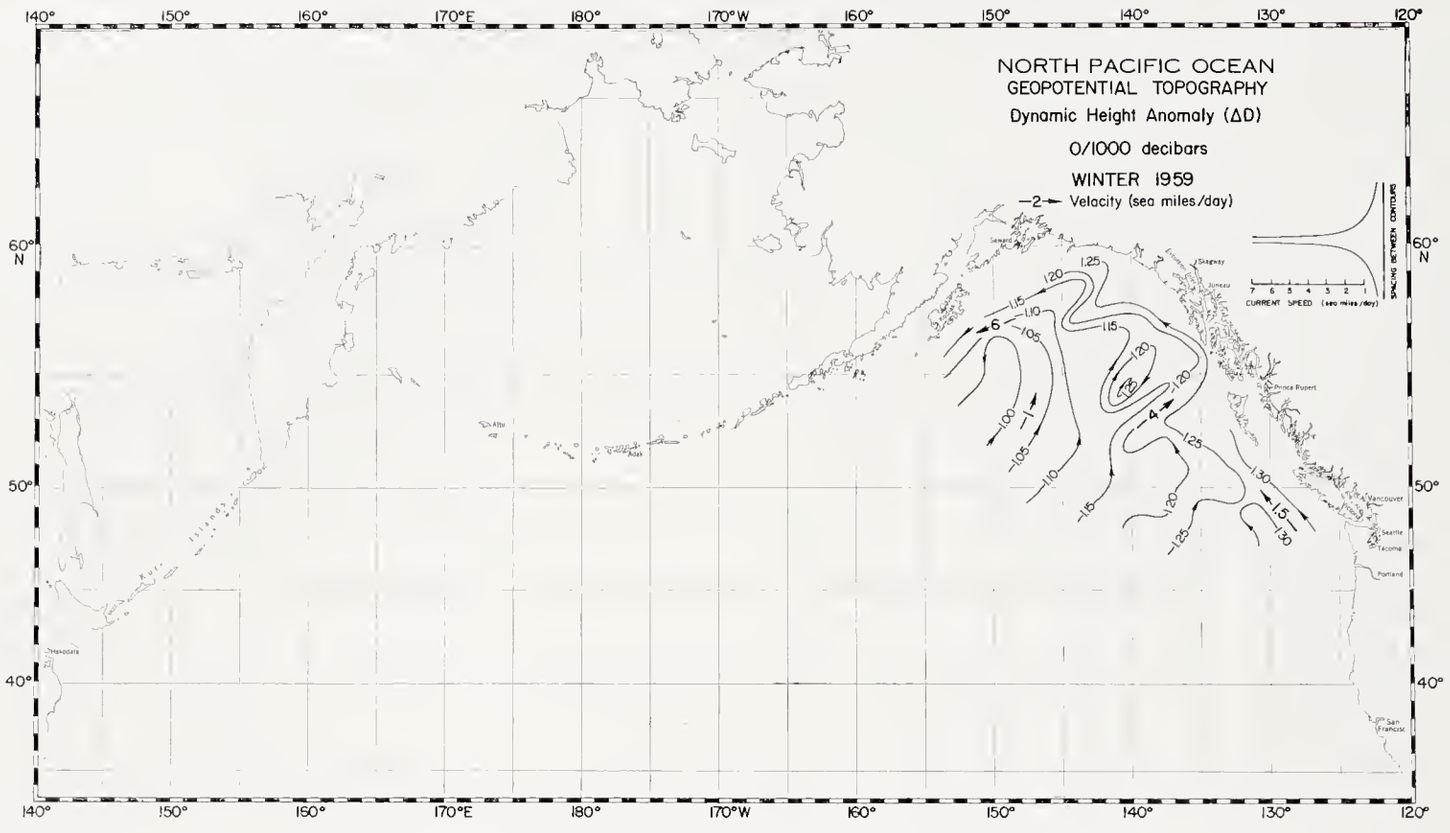


FIGURE 107. Geopotential topography, 0/1000 decibars, winter 1959.

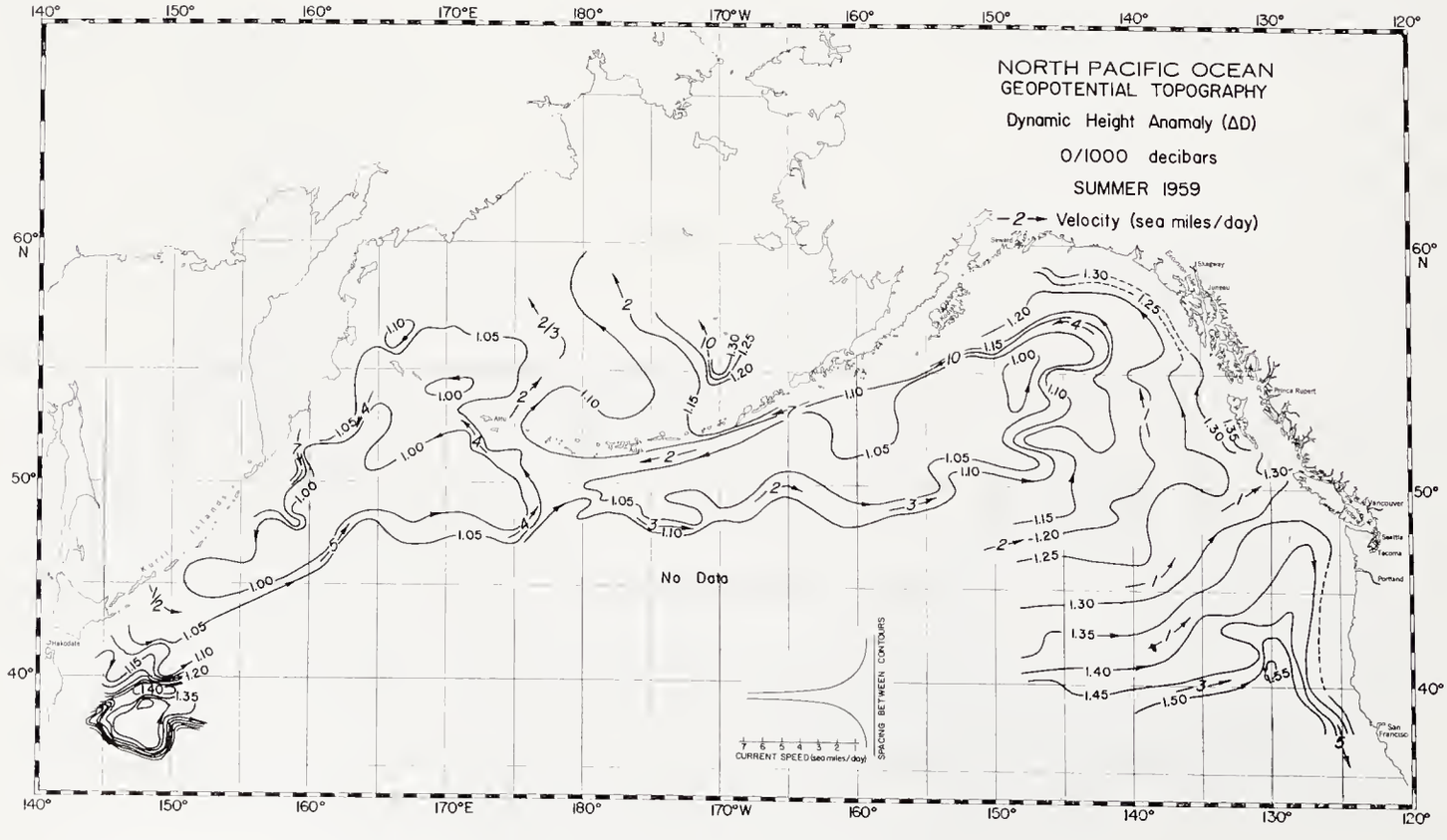


FIGURE 108. Geopotential topography, 0/1000 decibars, summer 1959.

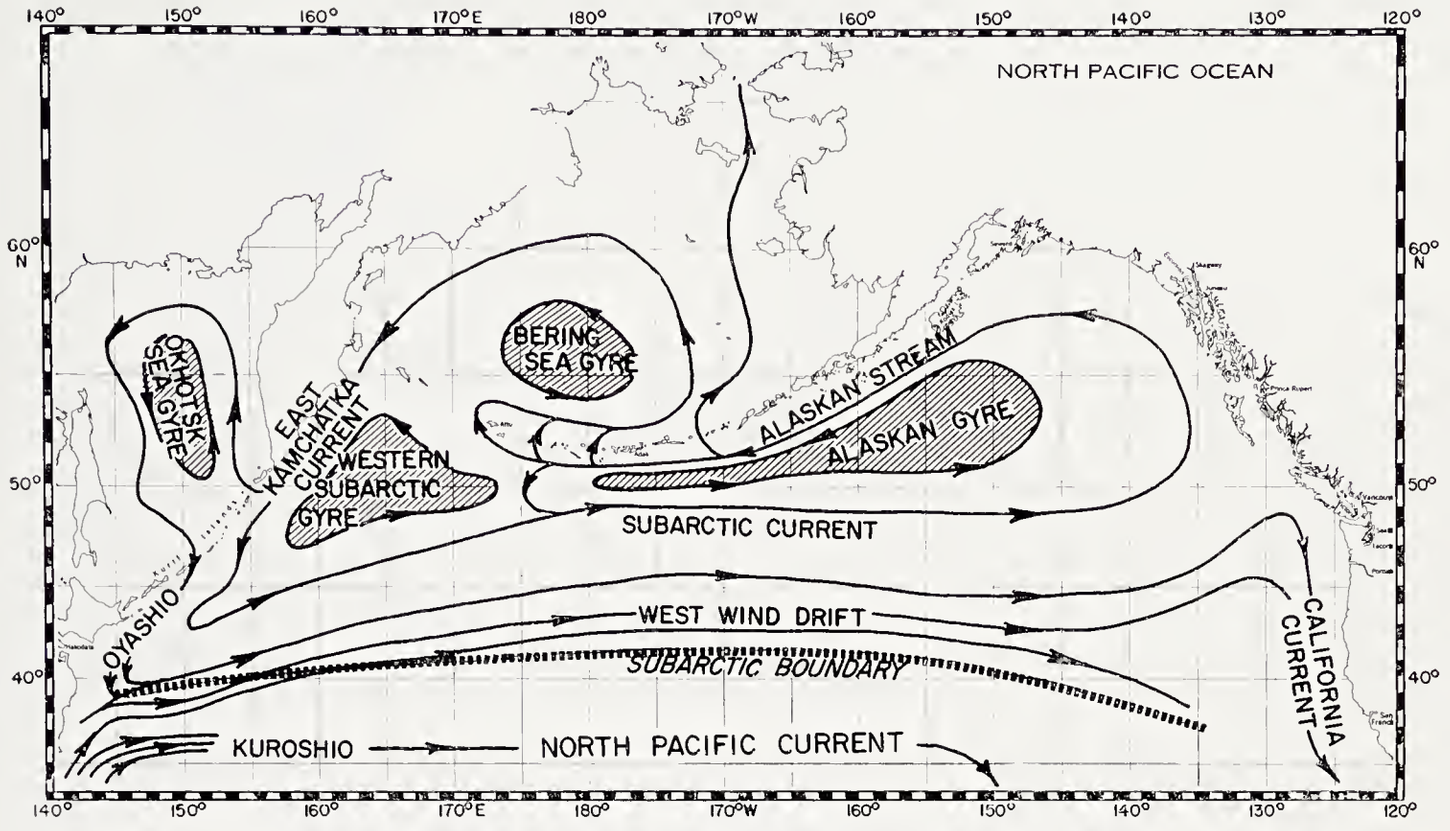


FIGURE 109. Schematic diagram of surface circulation relative to 1000 decibars.

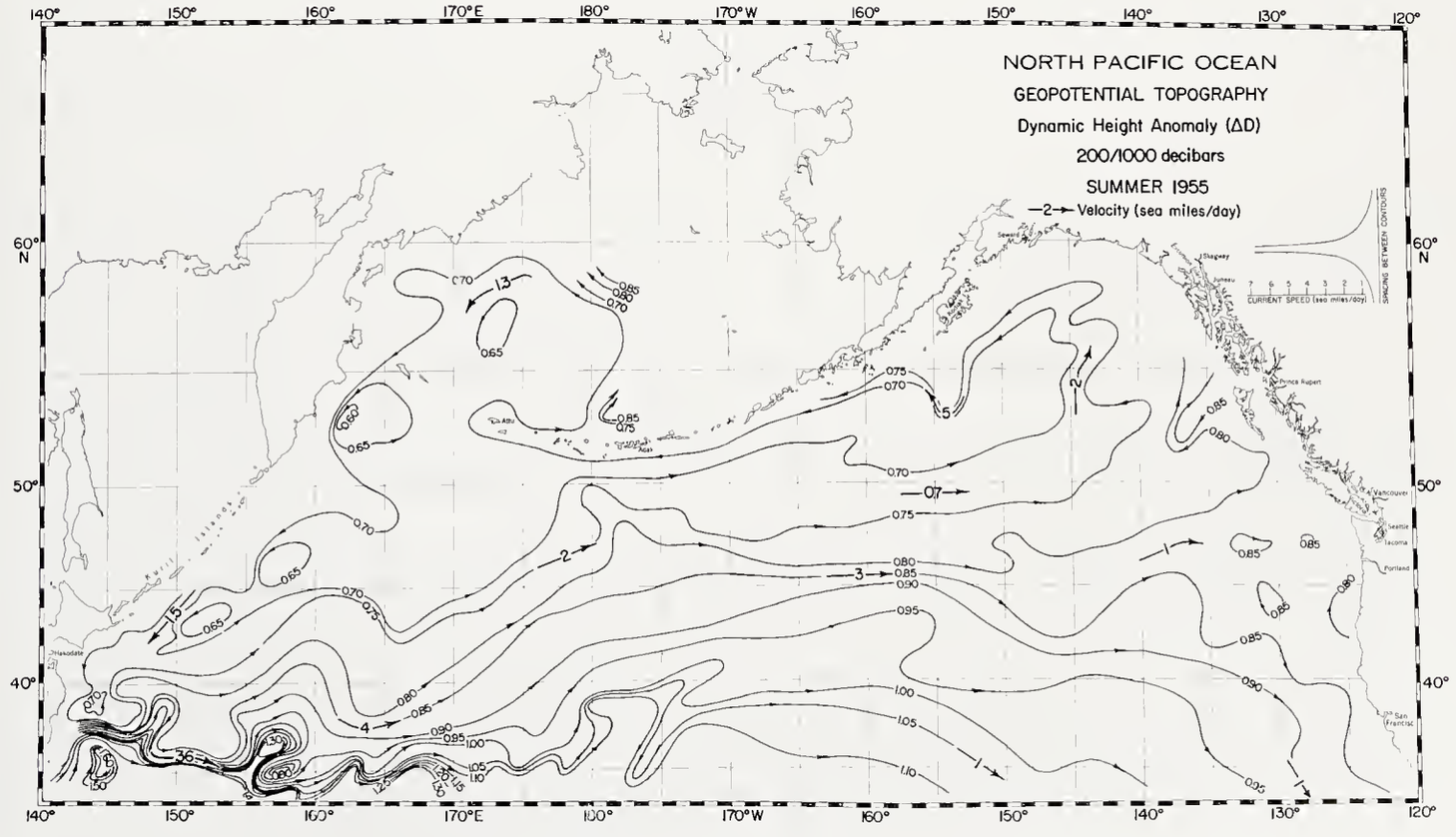


FIGURE 110. Geopotential topography, 200/1000 decibars, summer 1955.

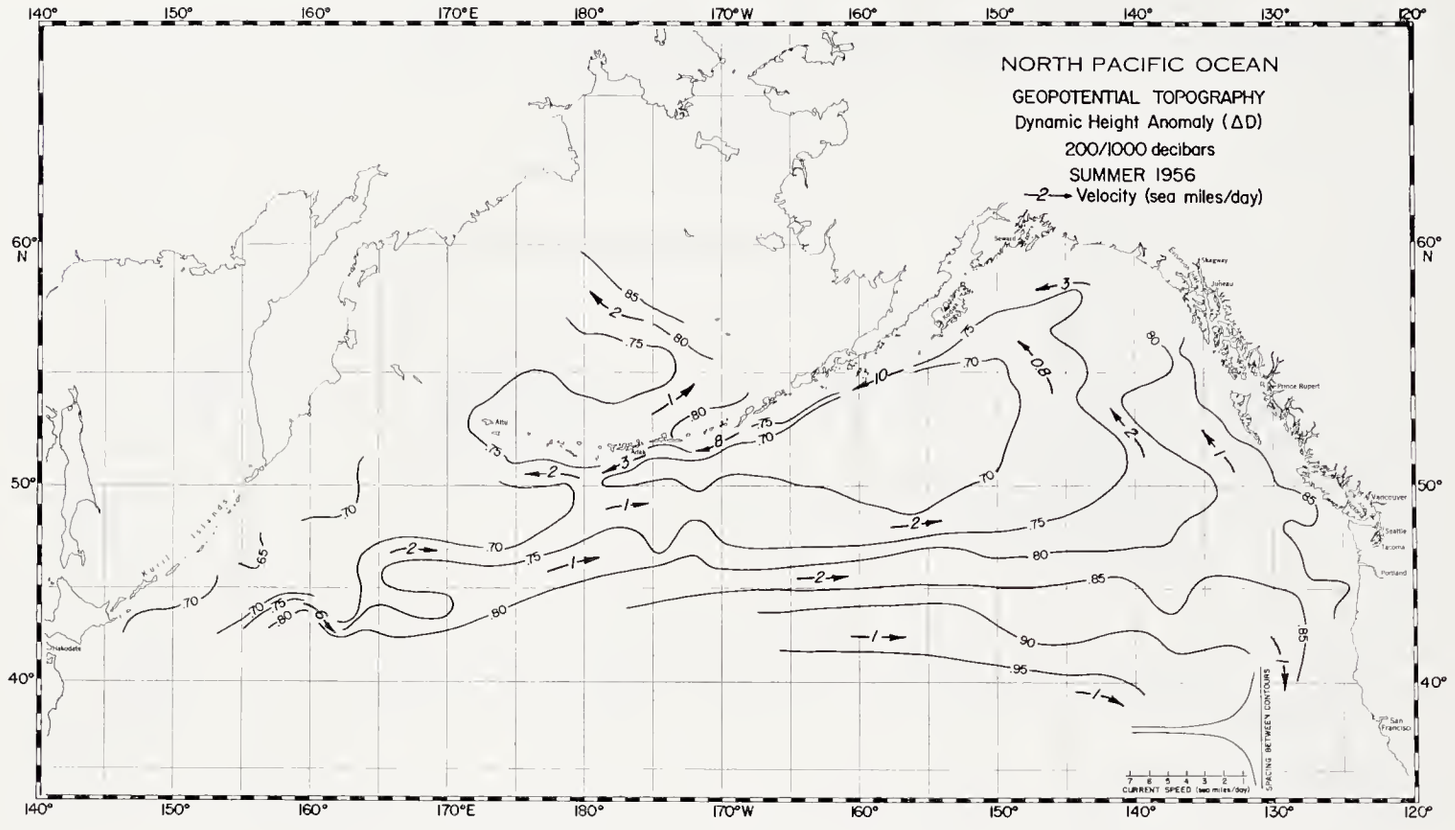


FIGURE 111. Geopotential topography, 200/1000 decibars, summer 1956.

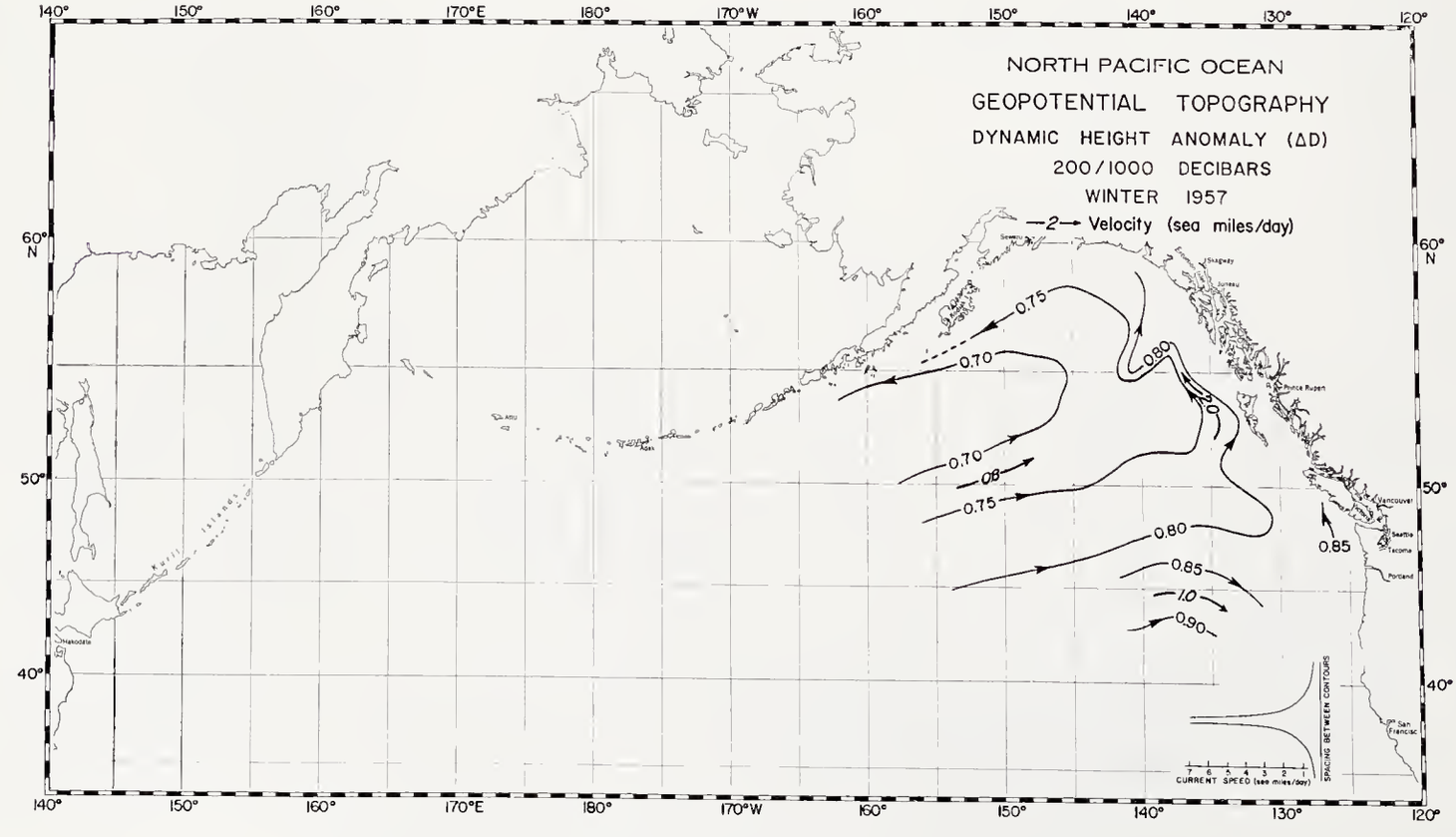


FIGURE 112. Geopotential topography, 200/1000 decibars, winter 1957.

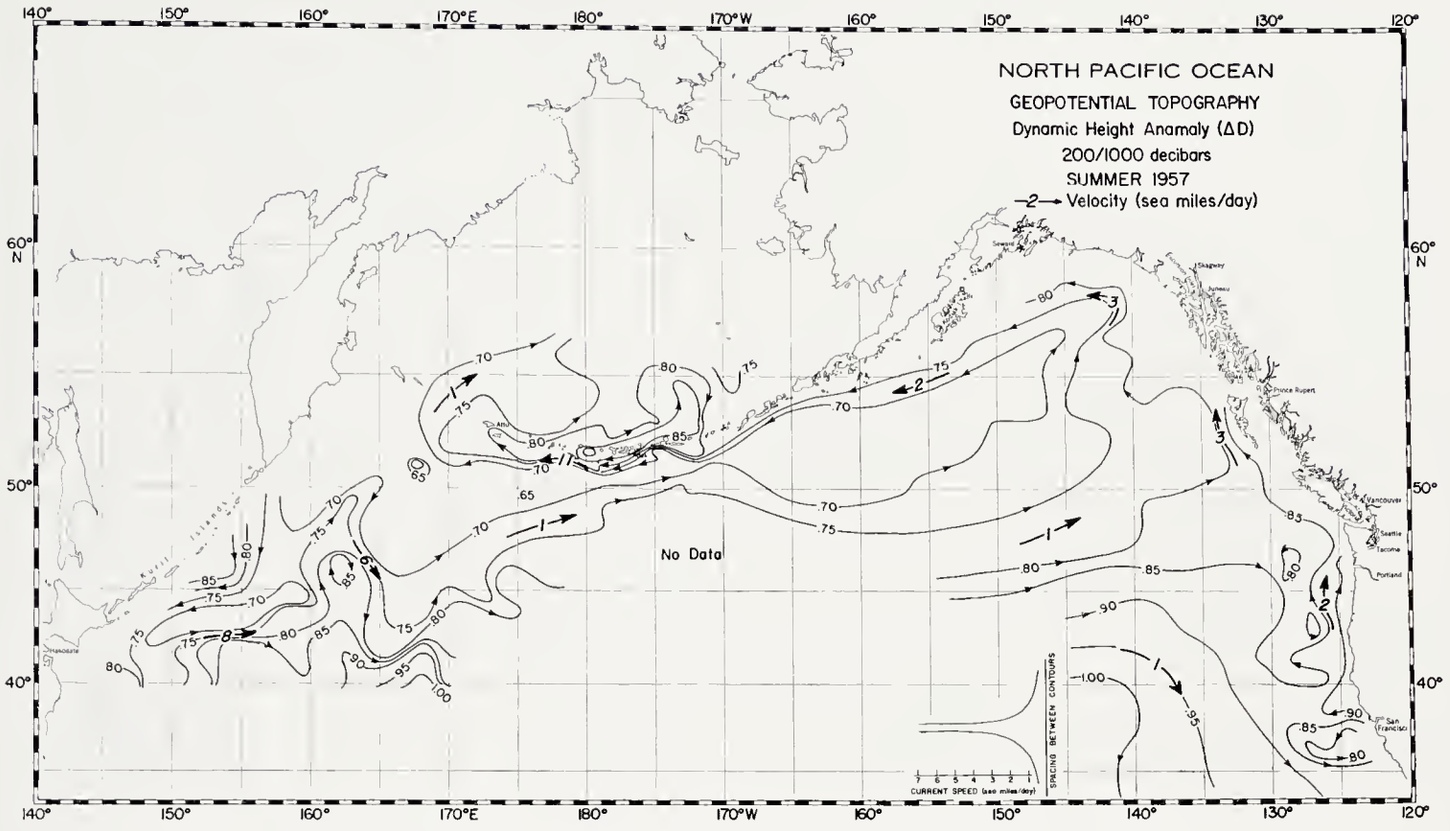


FIGURE 113. Geopotential topography, 200/1000 decibars, summer 1957.

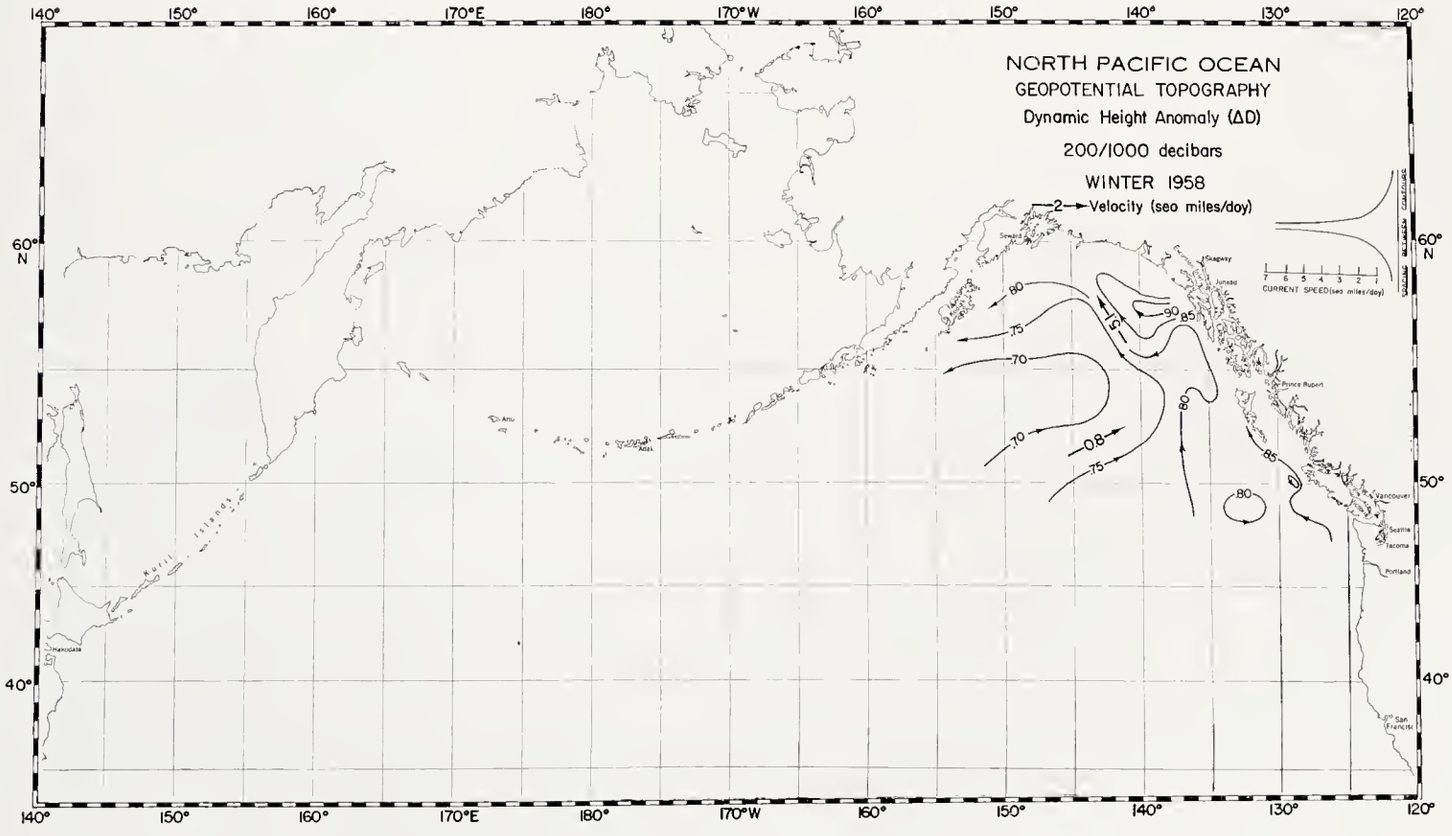


FIGURE 114. Geopotential topography, 200/1000 decibars, winter 1958.

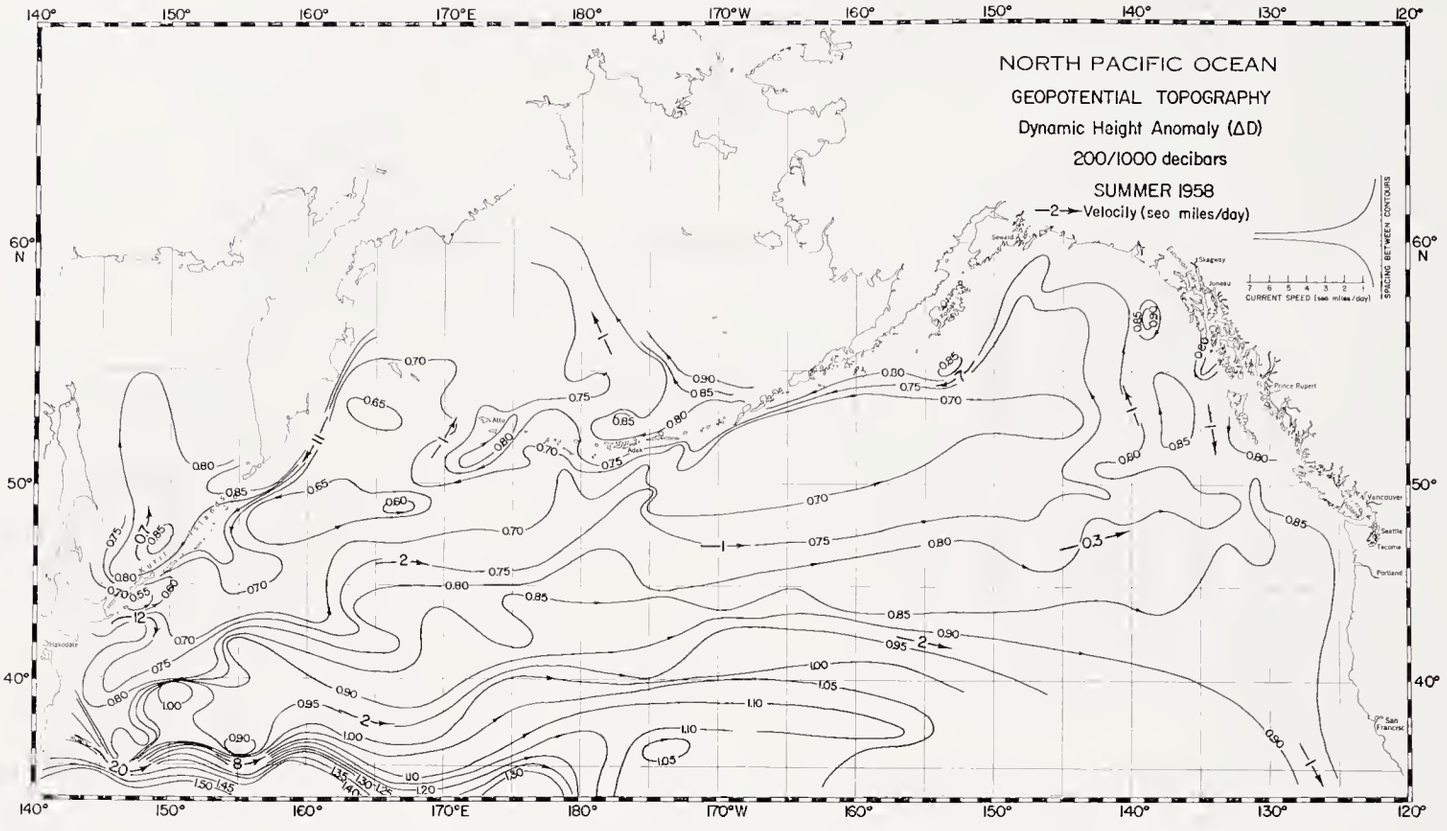


FIGURE 115. Geopotential topography, 200/1000 decibars, summer 1958.

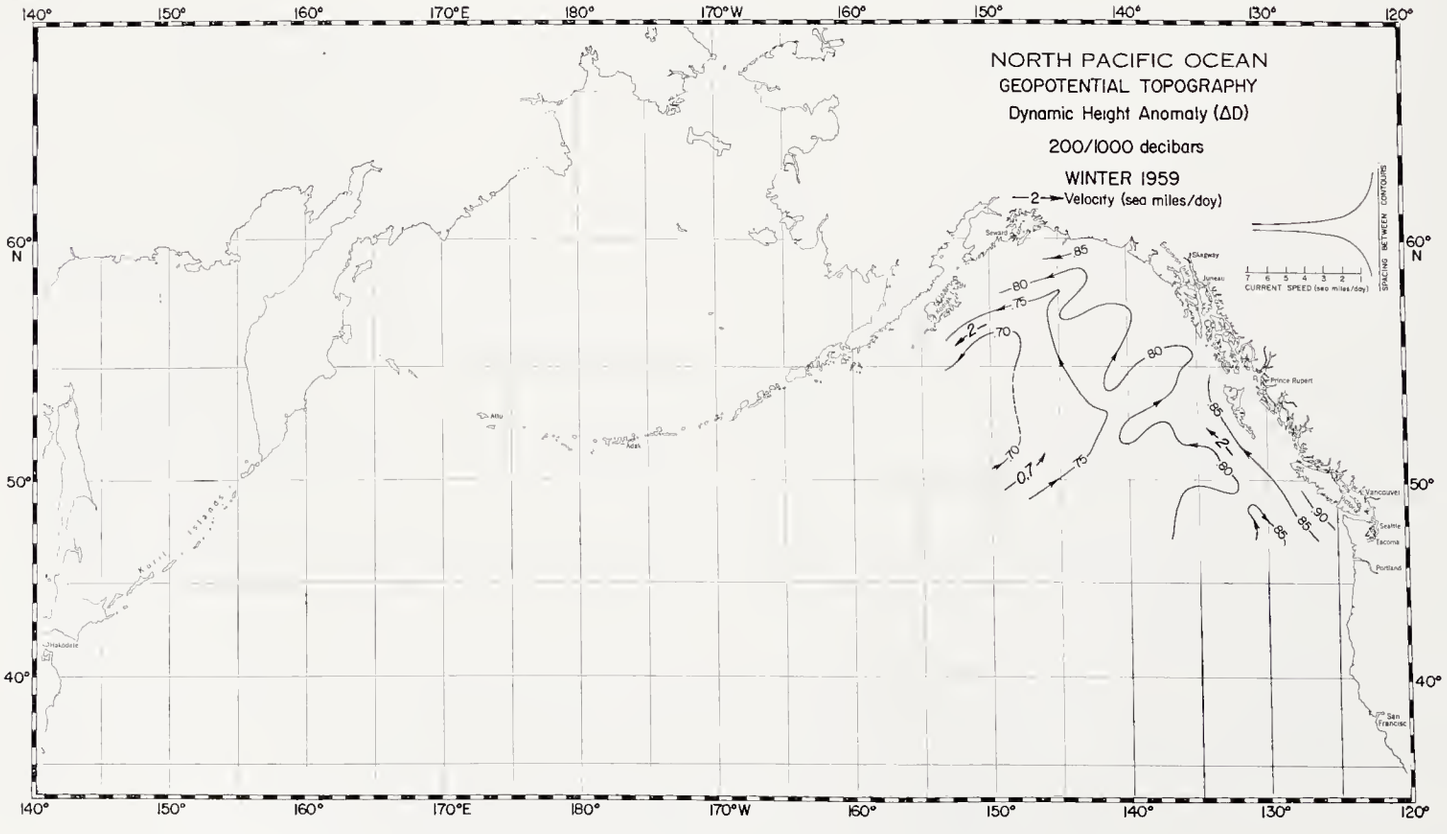


FIGURE 116. Geopotential topography, 200/1000 decibars, winter 1959.

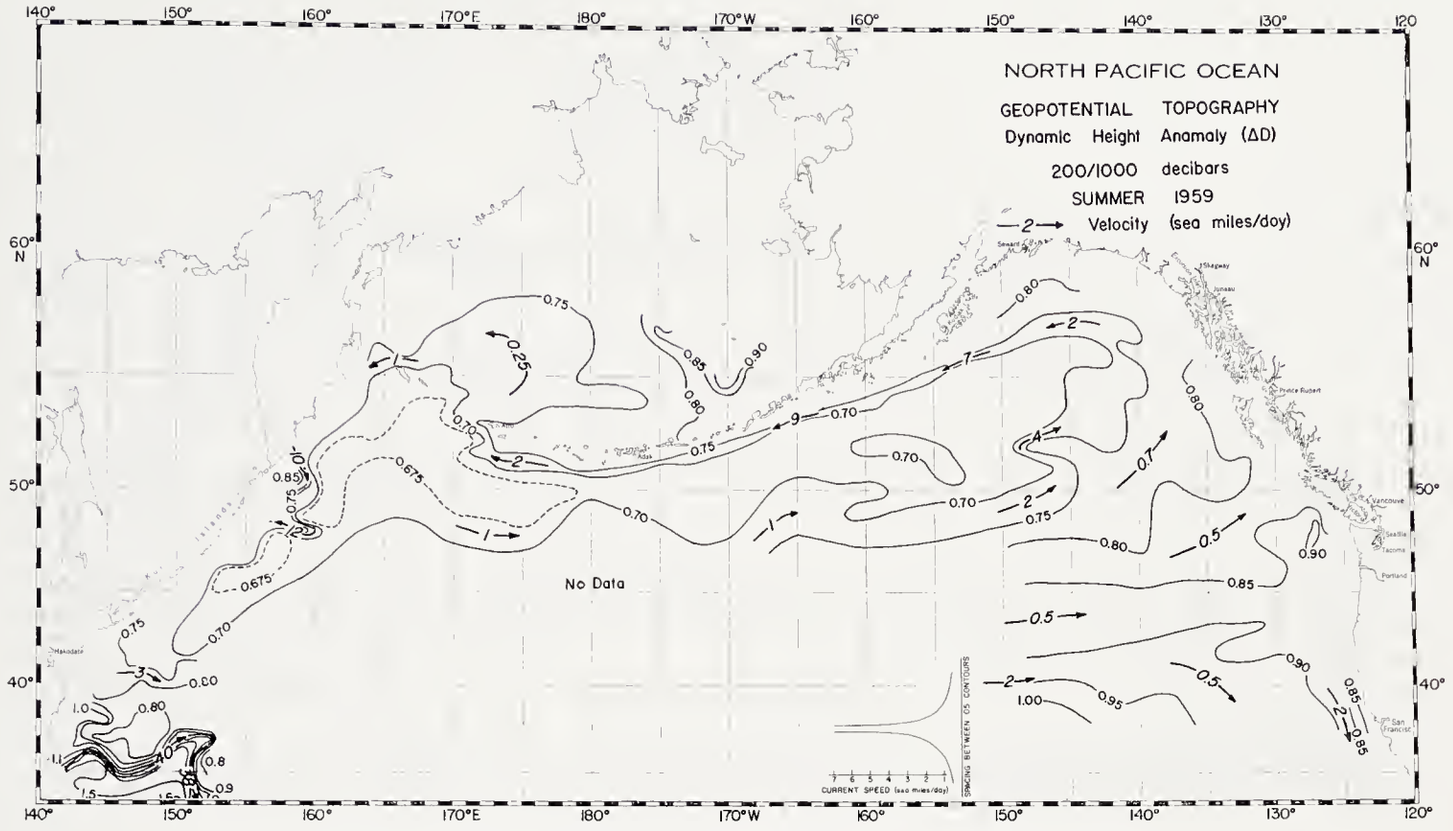


FIGURE 117. Geopotential topography, 200/1000 decibars, summer 1959.

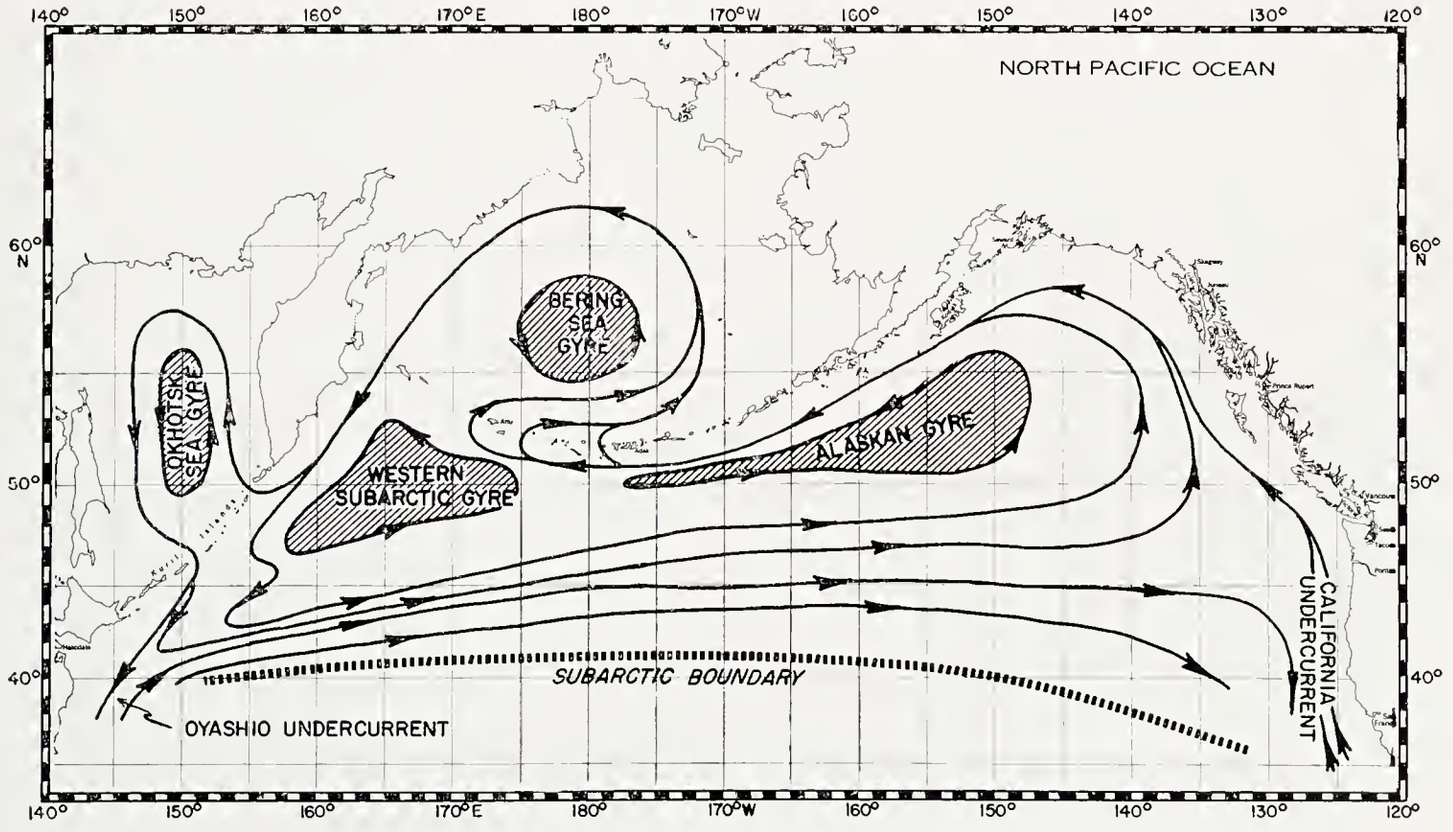


FIGURE 118. Schematic diagram of circulation at 200 decibars relative to 1000 decibars.

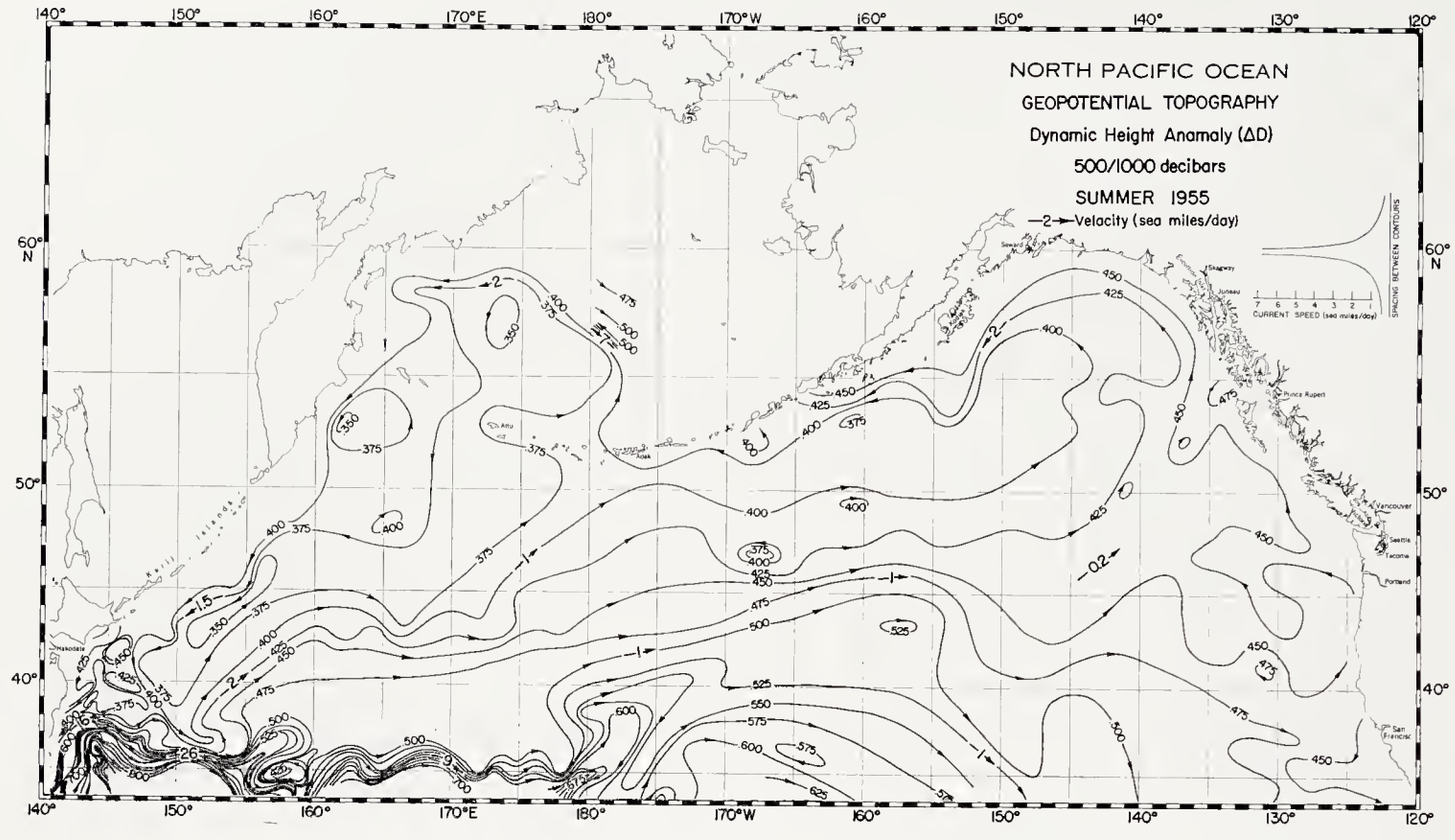


FIGURE 119. Geopotential topography, 500/1000 decibars, summer 1955.

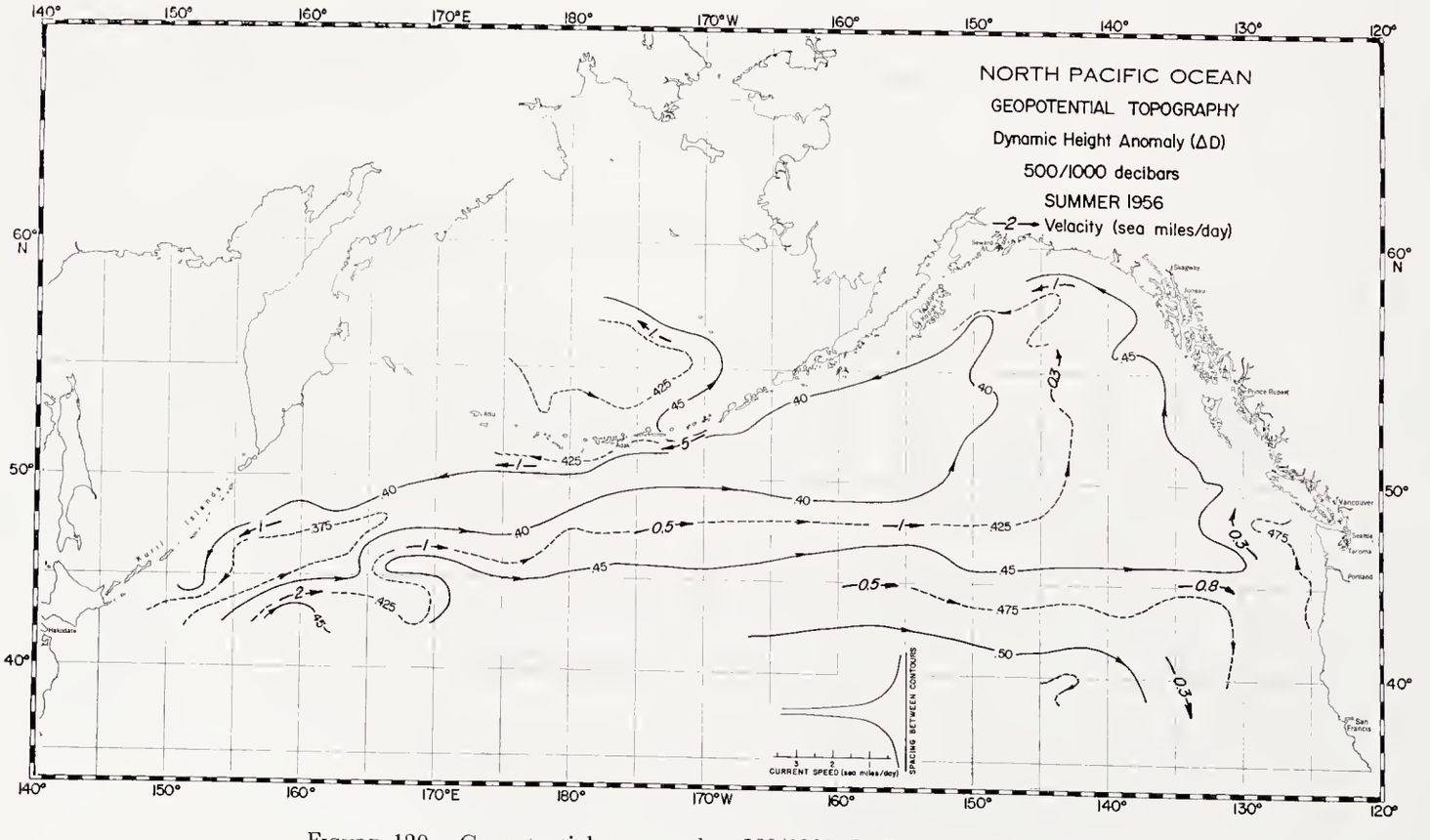


FIGURE 120. Geopotential topography, 500/1000 decibars, summer 1956.

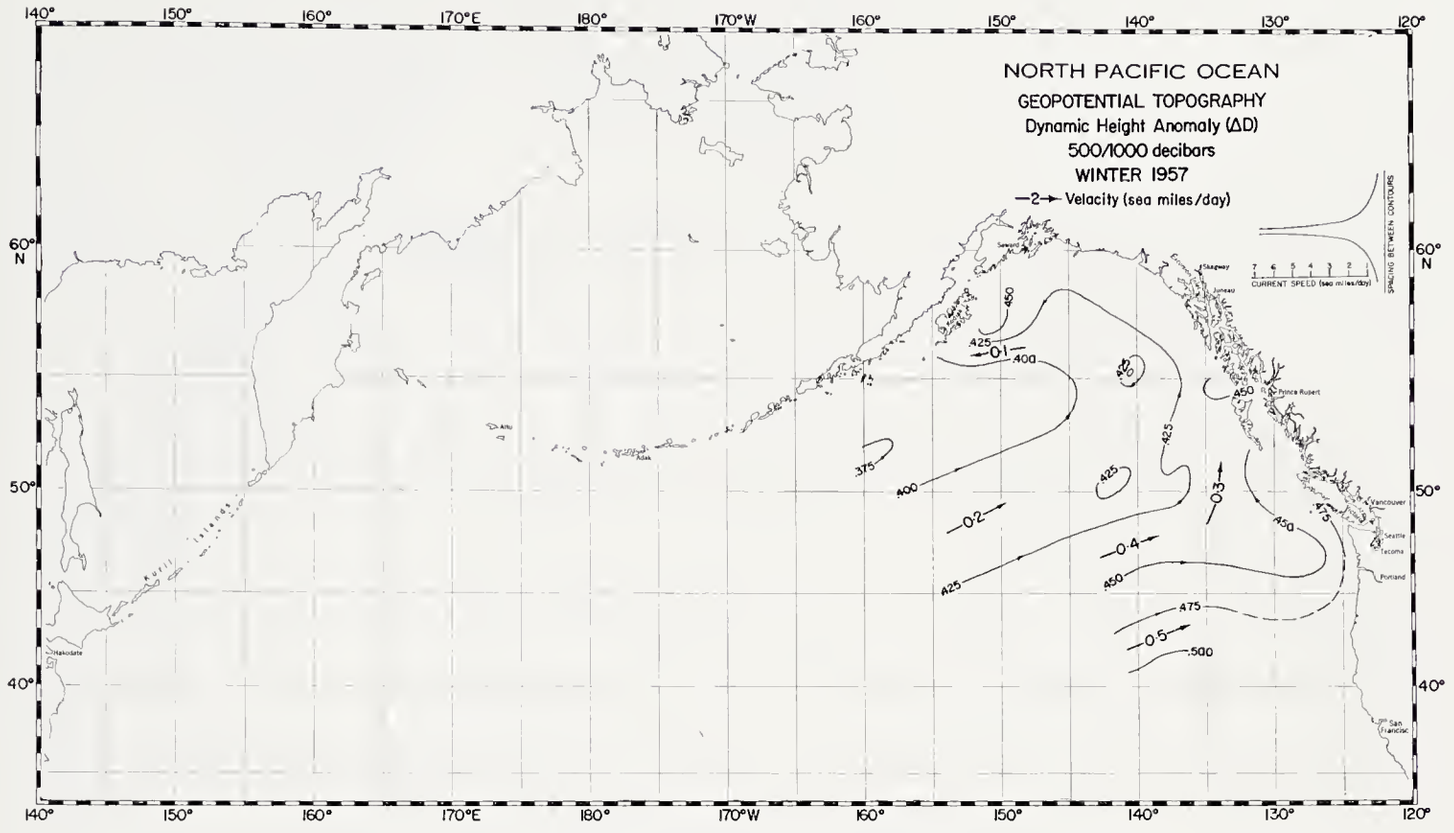


FIGURE 121. Geopotential topography, 500/1000 decibars, winter 1957.

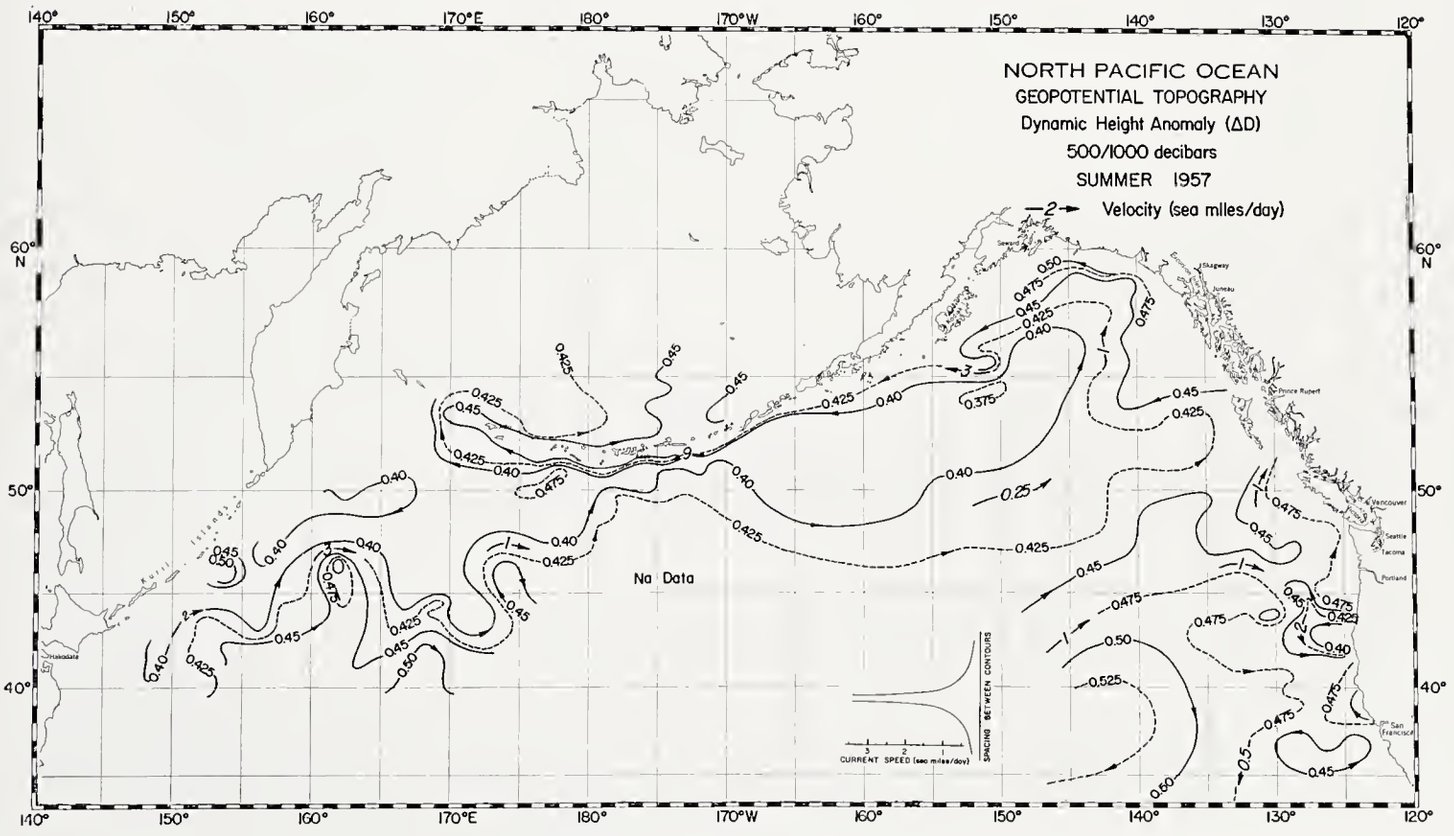


FIGURE 122. Geopotential topography, 500/1000 decibars, summer 1957.

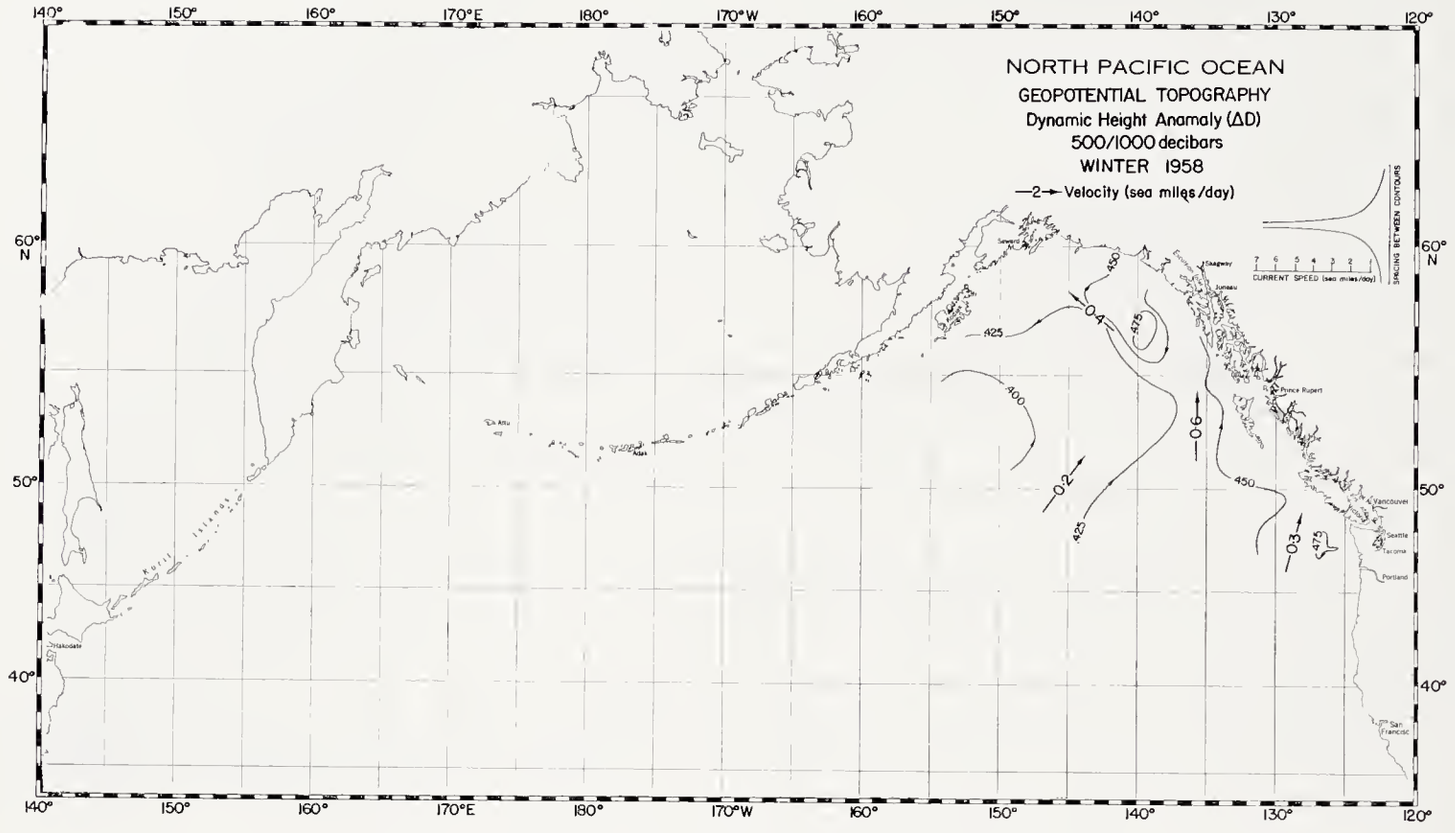


FIGURE 123. Geopotential topography, 500/1000 decibars, winter 1958.

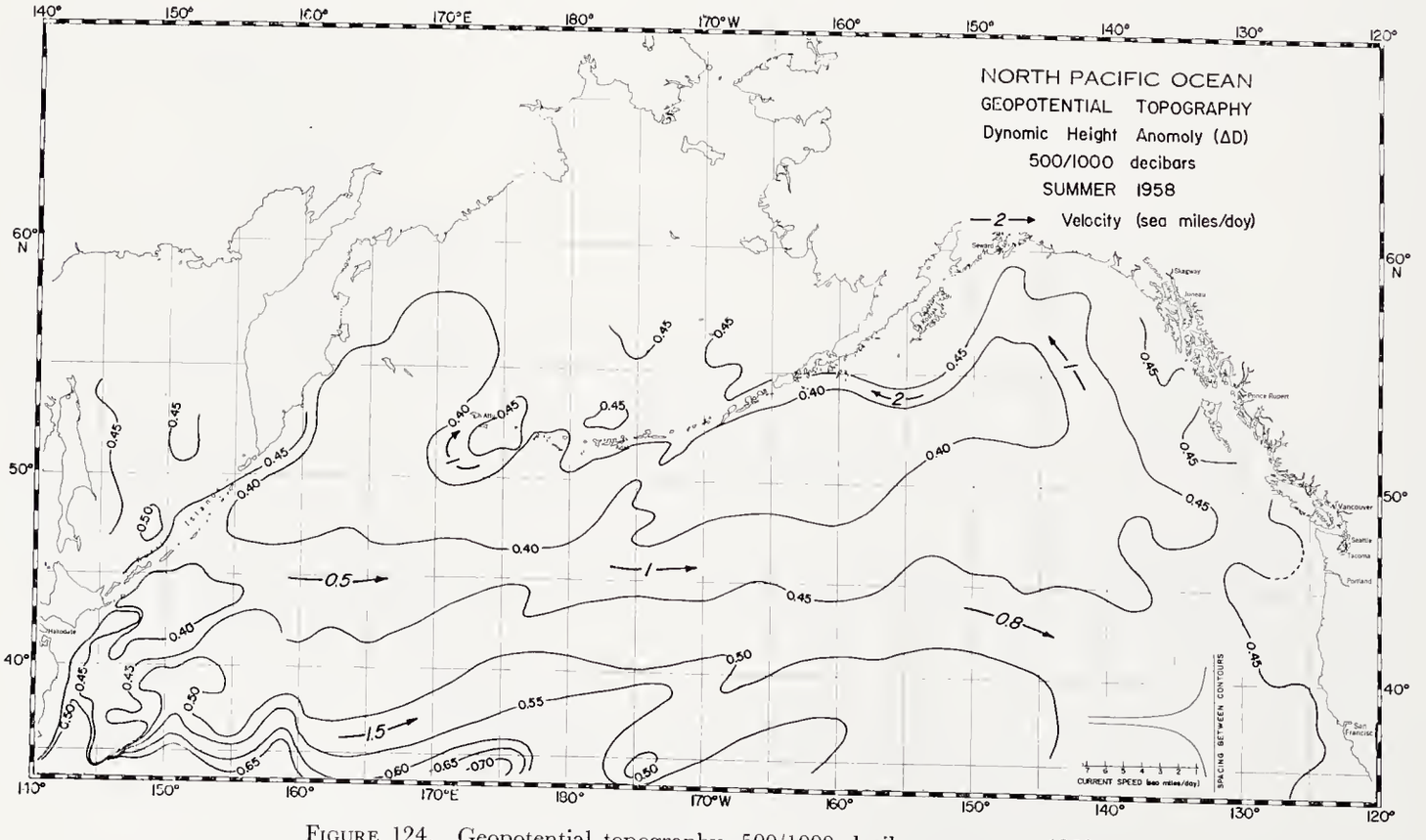


FIGURE 124. Geopotential topography, 500/1000 decibars, summer 1958.

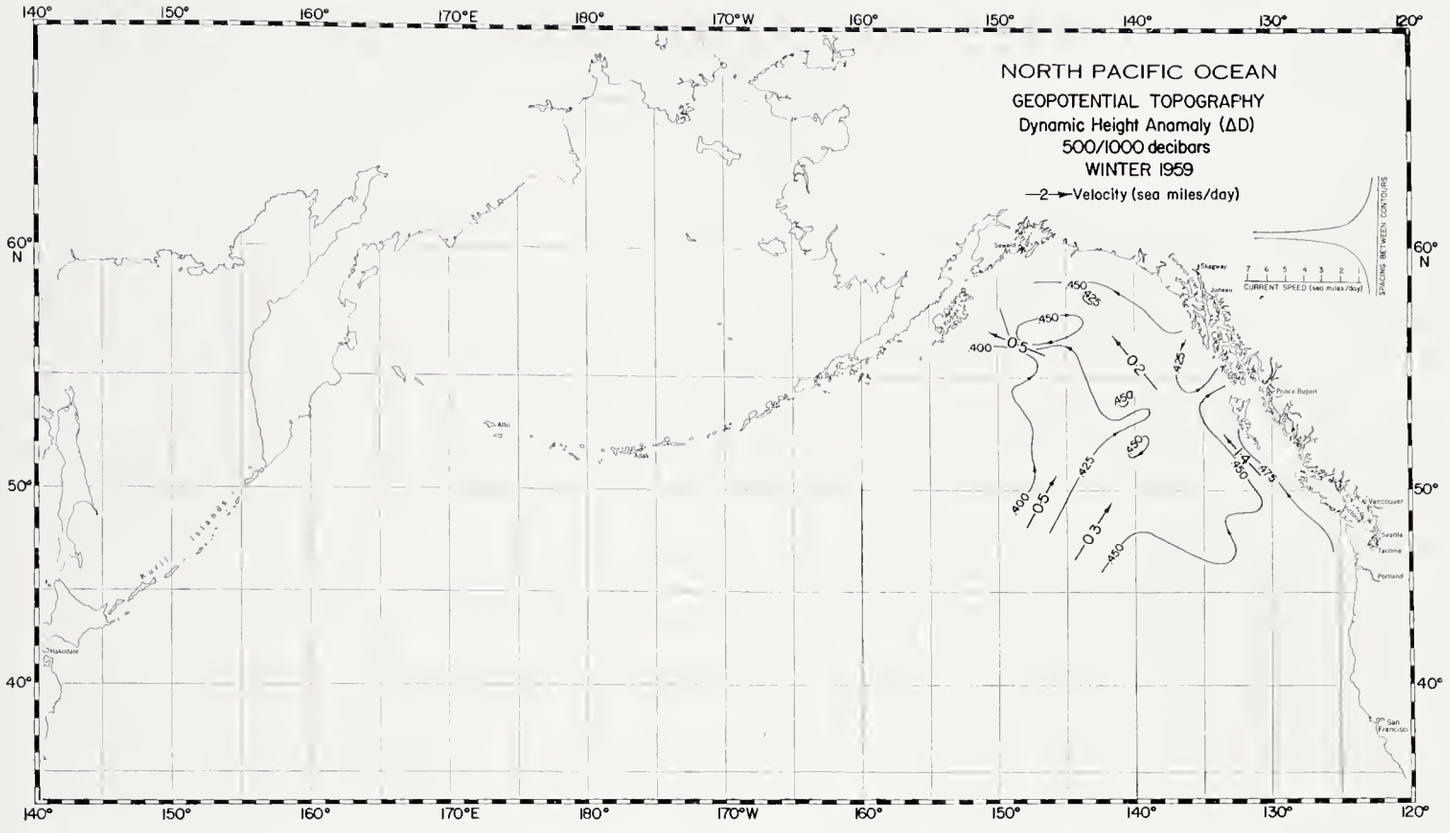


FIGURE 125. Geopotential topography, 500/1000 decibars, winter 1959.

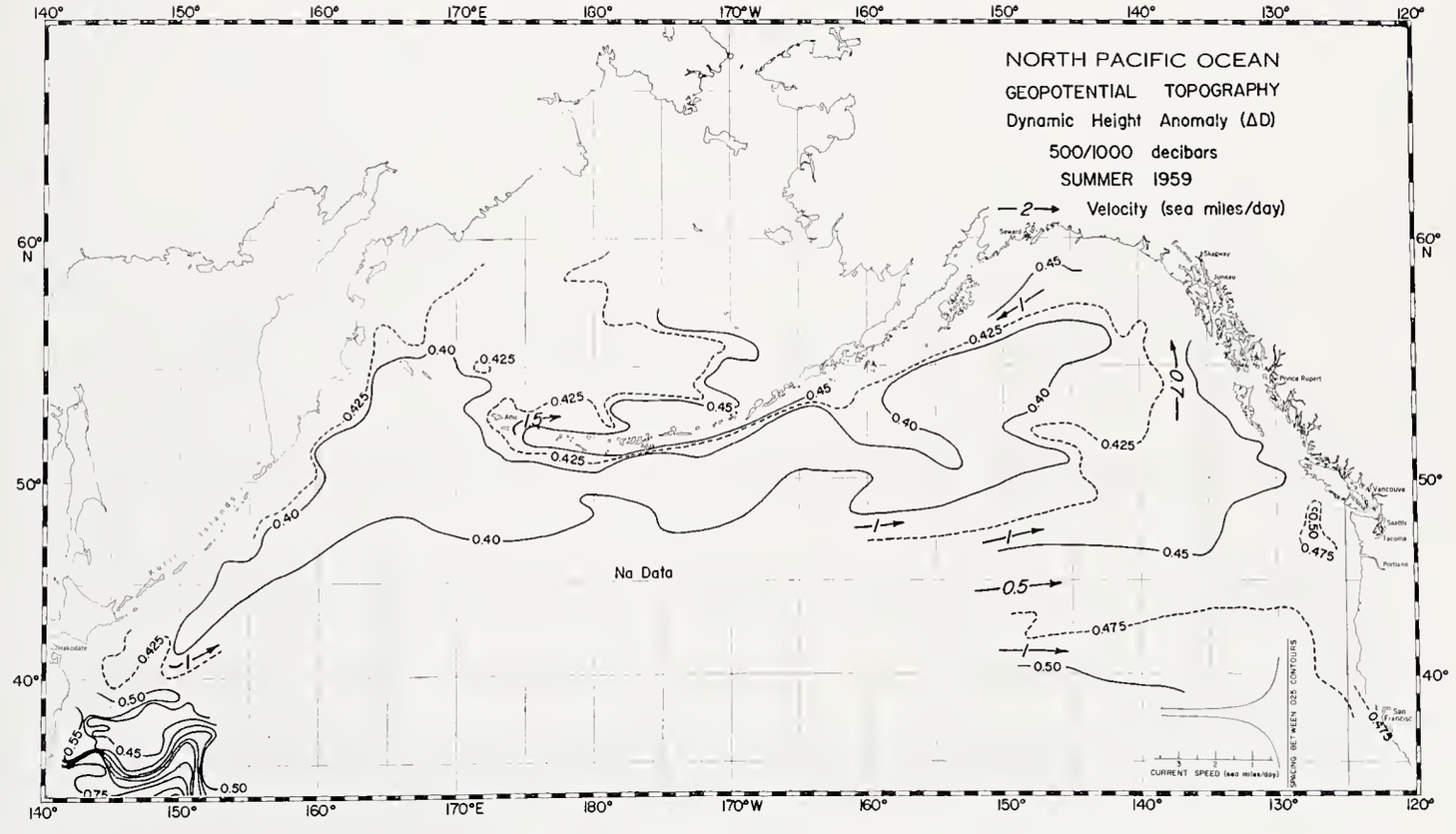


FIGURE 126. Geopotential topography, 500/1000 decibars, summer 1959.

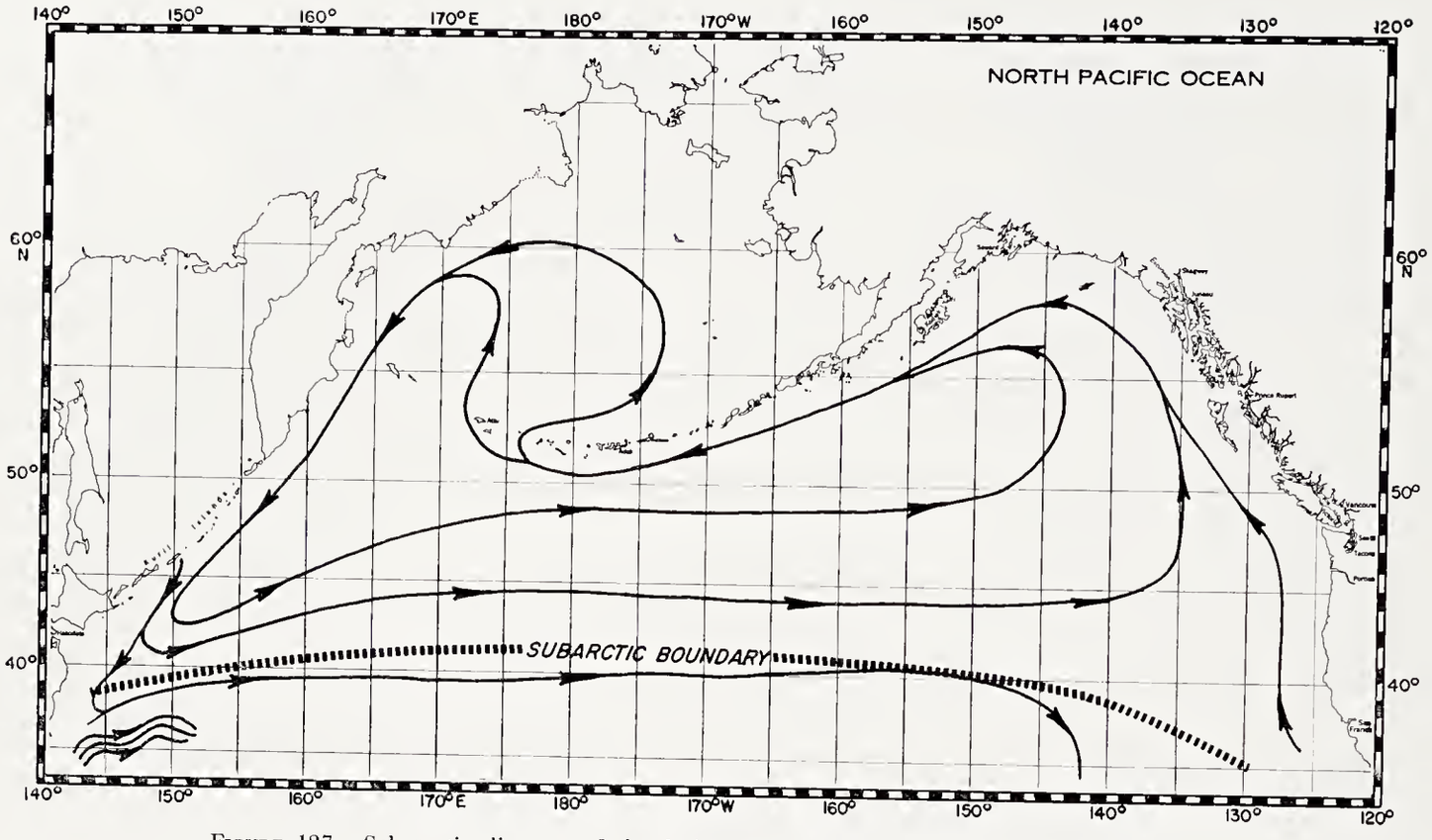


FIGURE 127. Schematic diagram of circulation at 500 decibars relative to 1000 decibars.

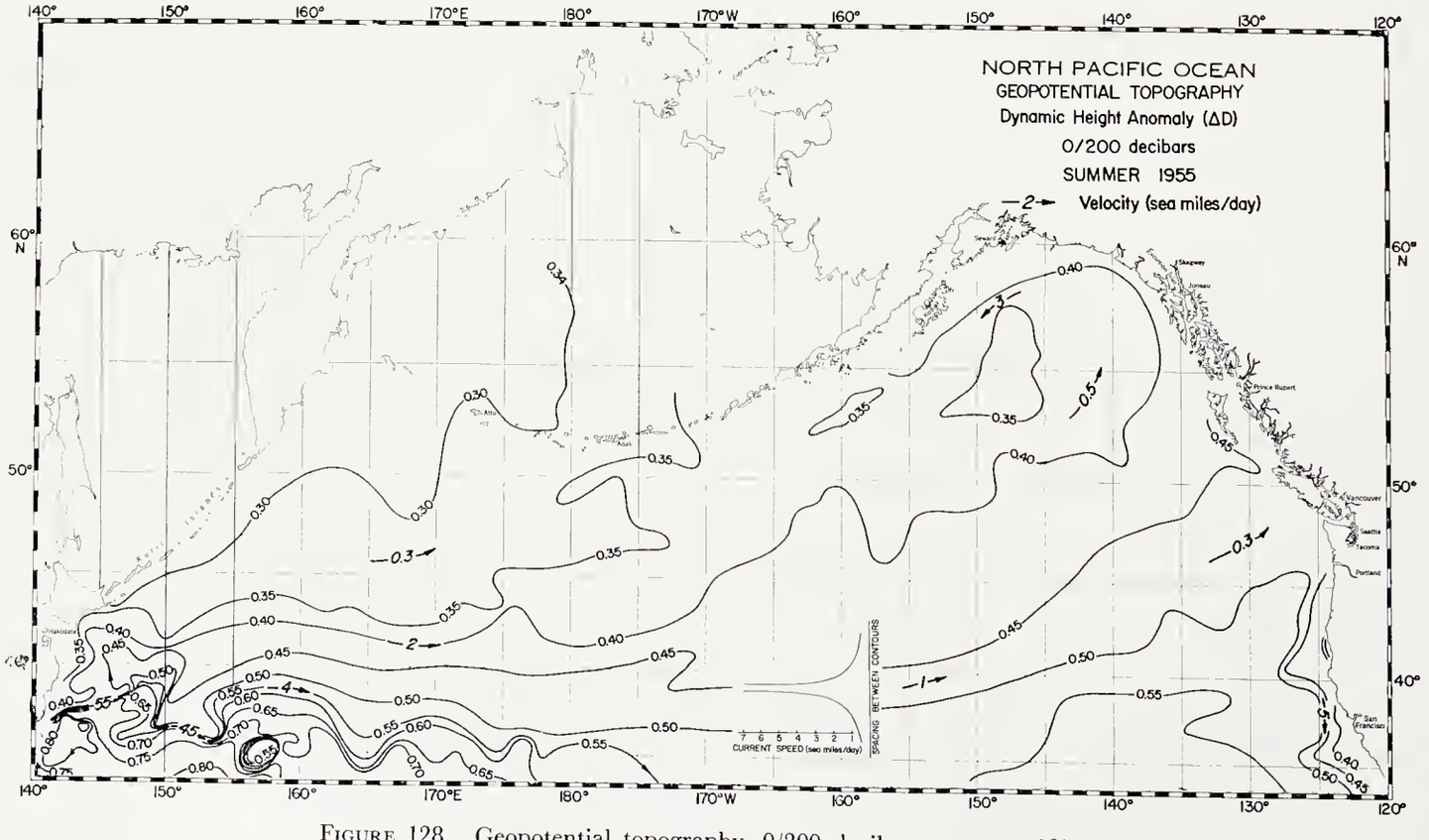


FIGURE 128. Geopotential topography, 0/200 decibars, summer 1955.

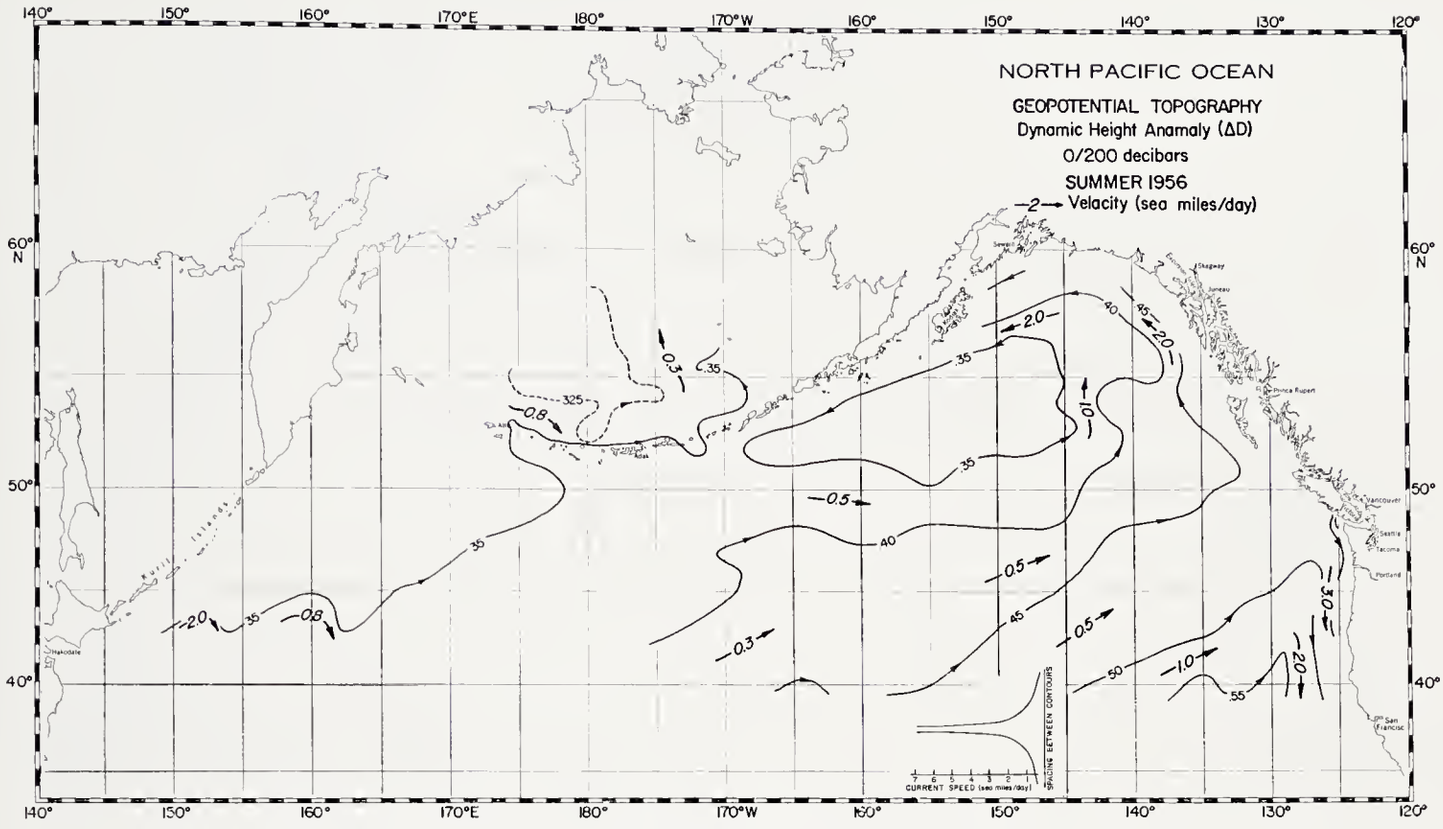


FIGURE 129. Geopotential topography, 0/200 decibars, summer 1956.

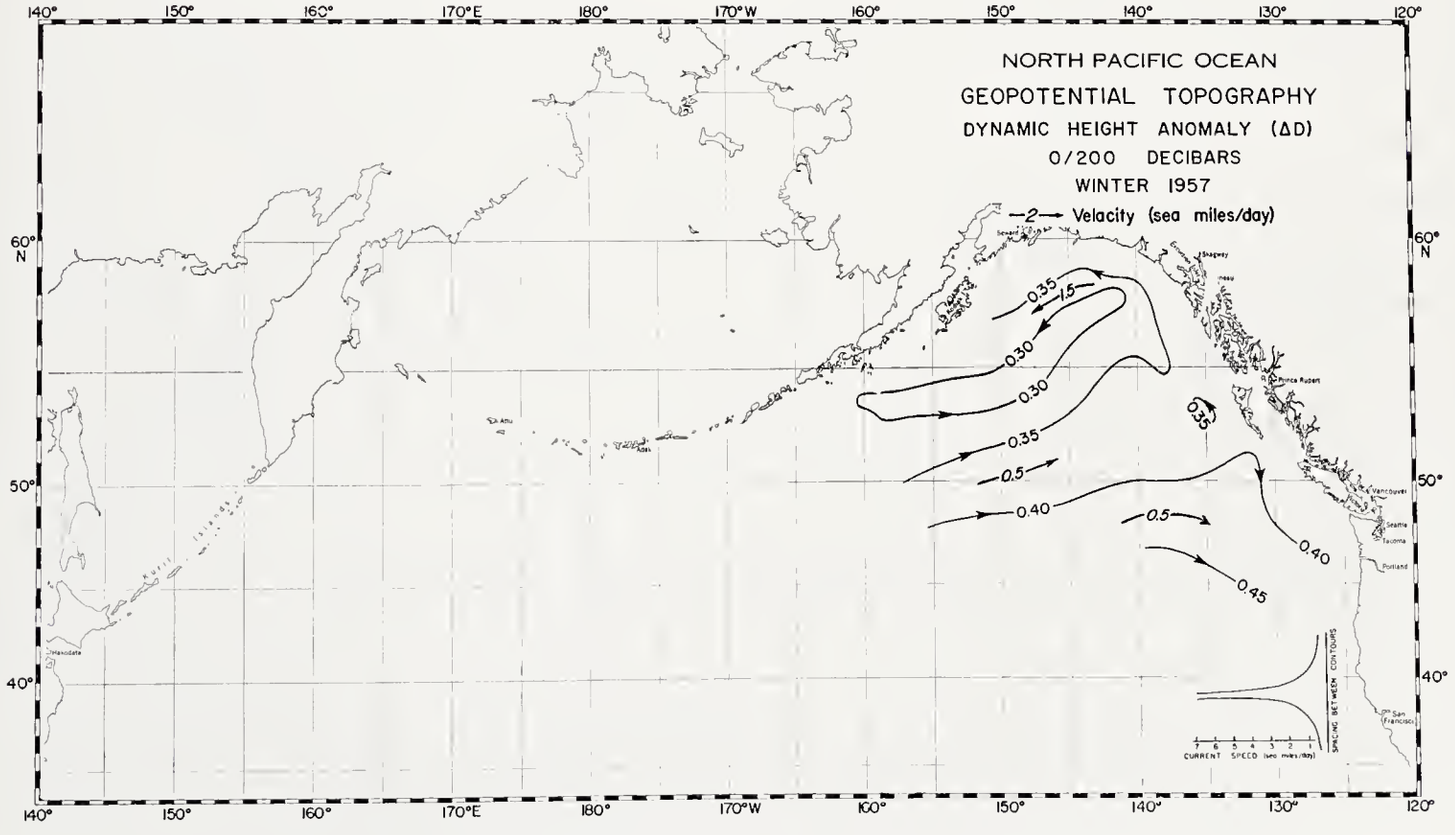


FIGURE 130. Geopotential topography, 0/200 decibars, winter 1957.

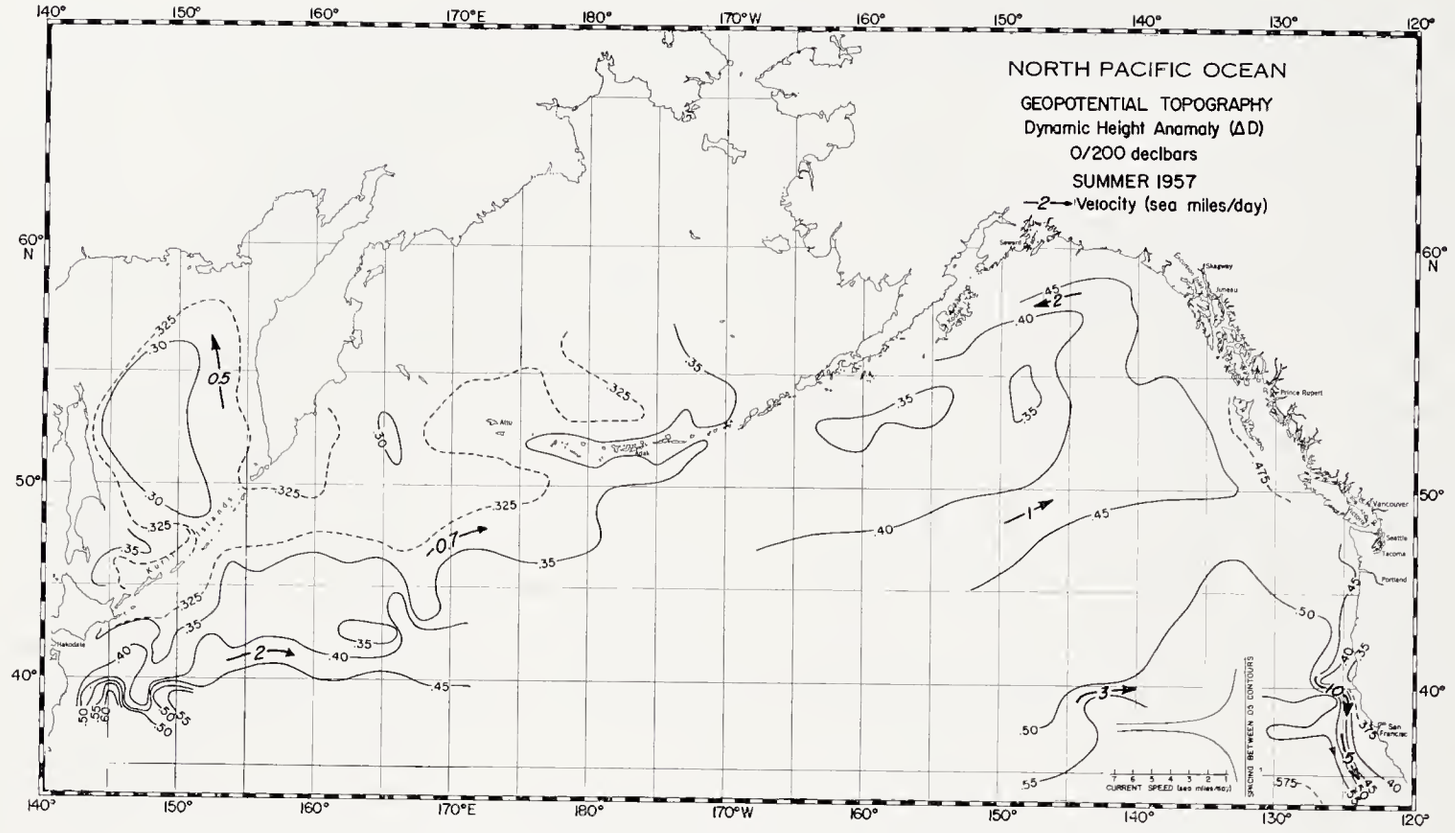


FIGURE 131. Geopotential topography, 0/200 decibars, summer 1957.

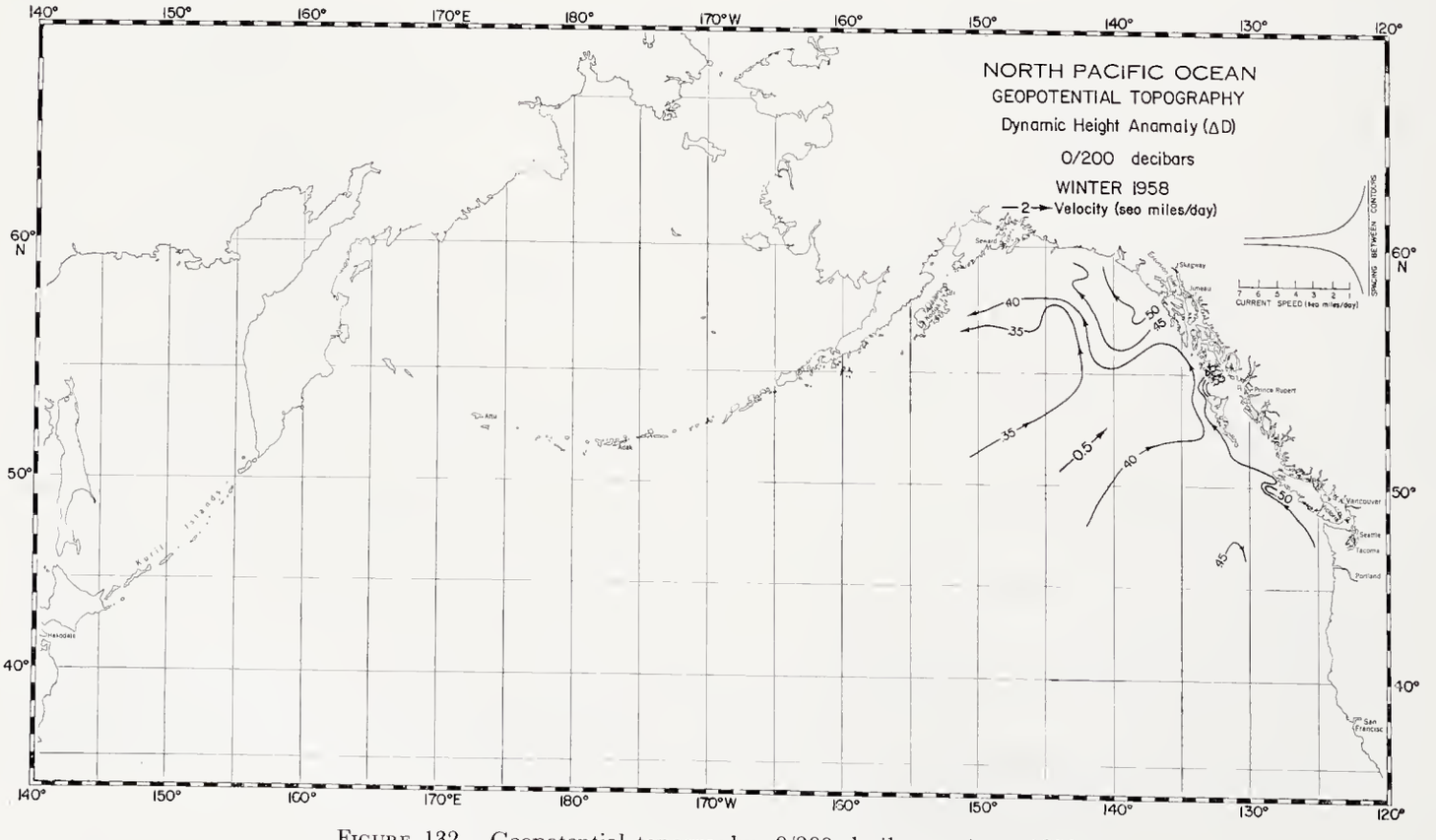


FIGURE 132. Geopotential topography, 0/200 decibars, winter 1958.

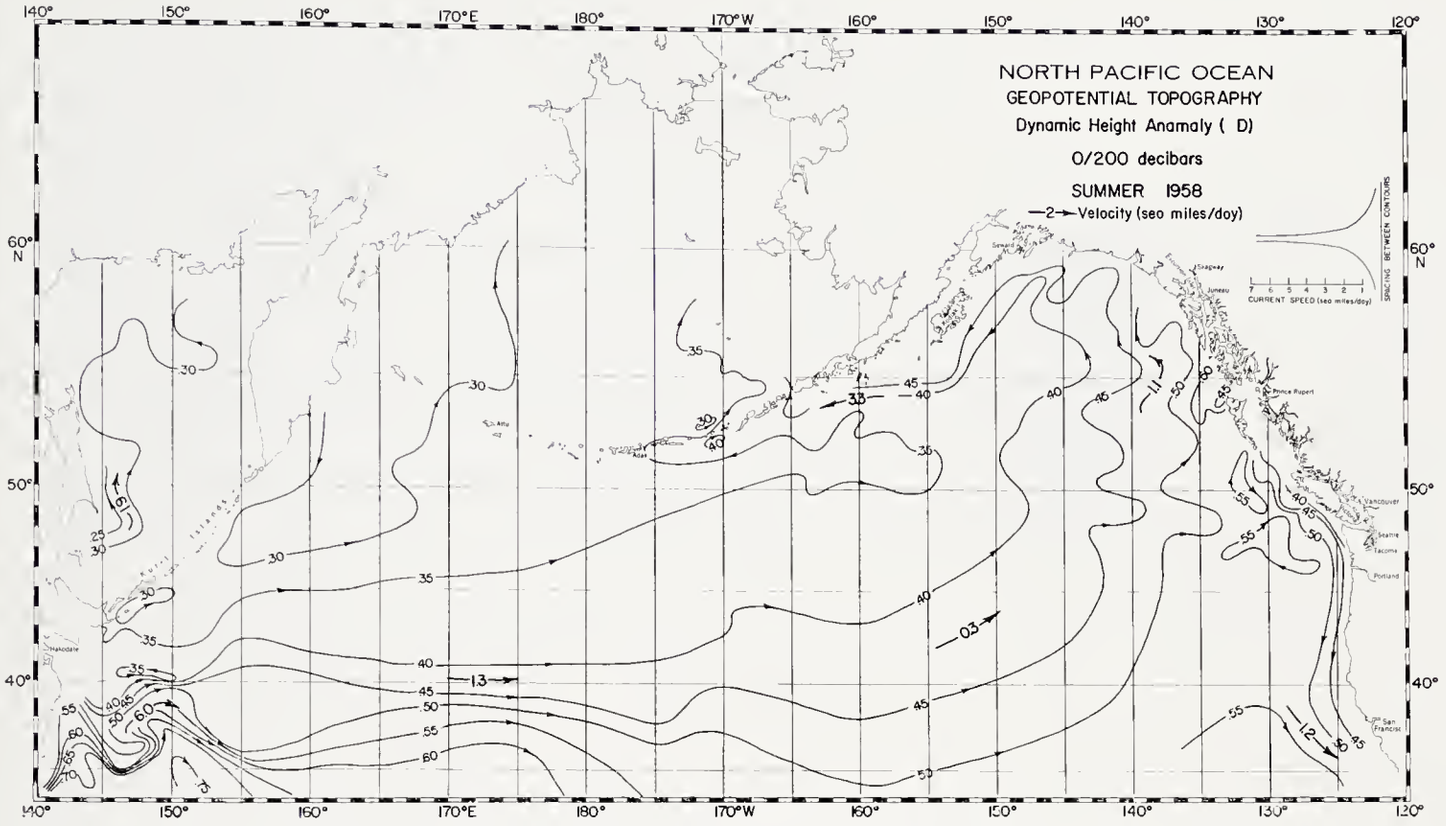


FIGURE 133. Geopotential topography, 0/200 decibars, summer 1958.

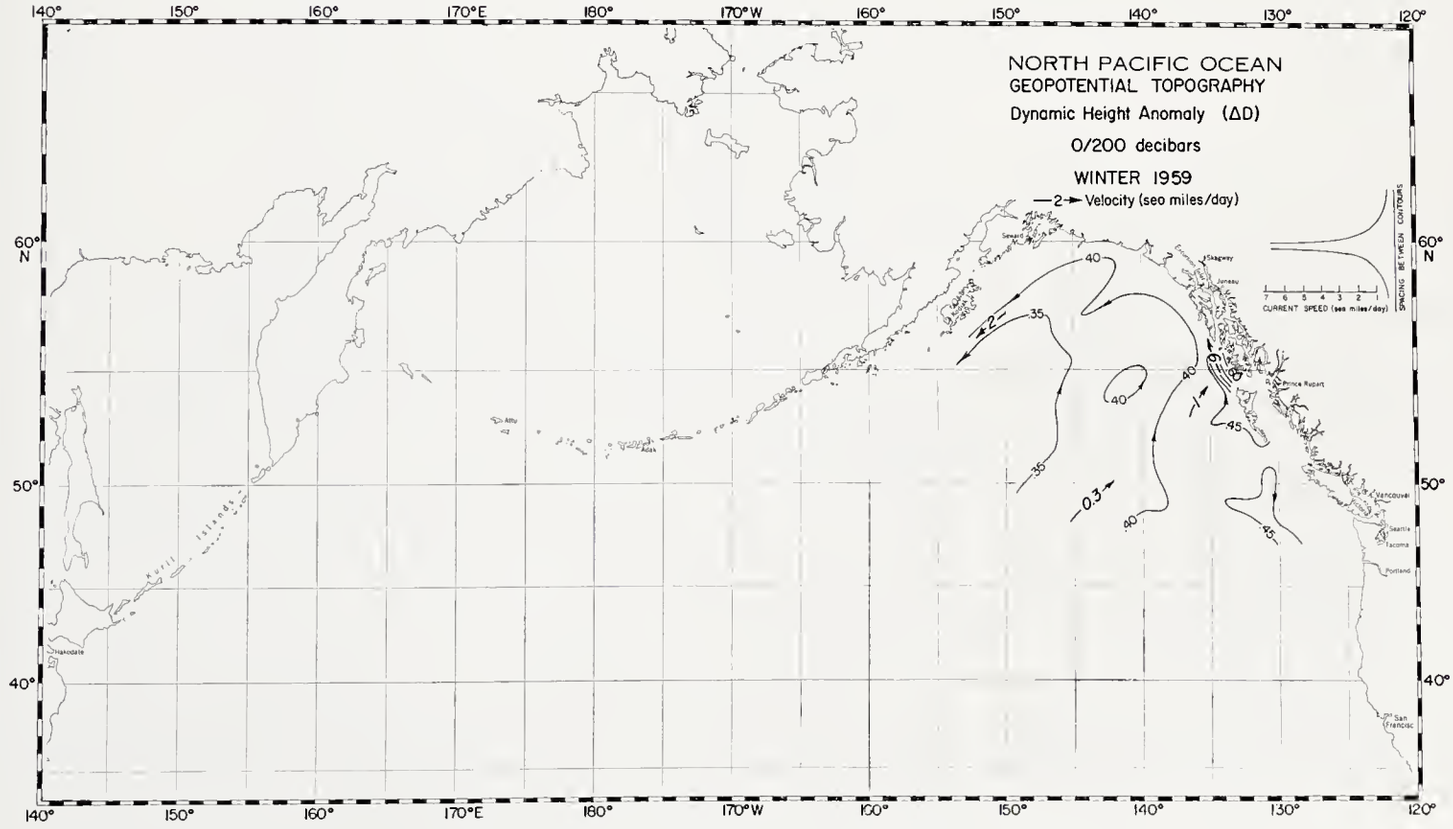


FIGURE 134. Geopotential topography, 0/200 decibars, winter 1959.

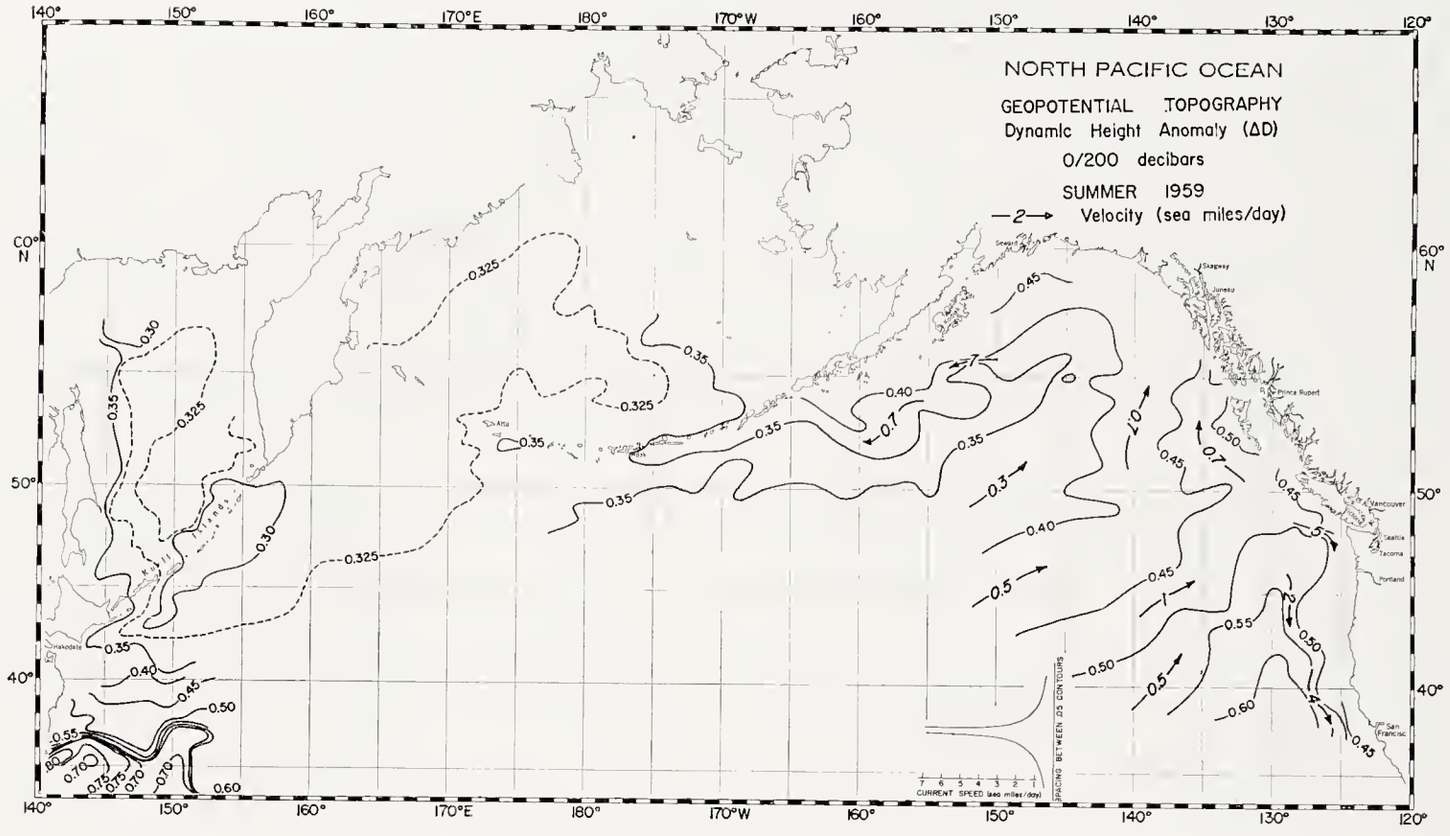


FIGURE 135. Geopotential topography, 0/200 decibars, summer 1959.

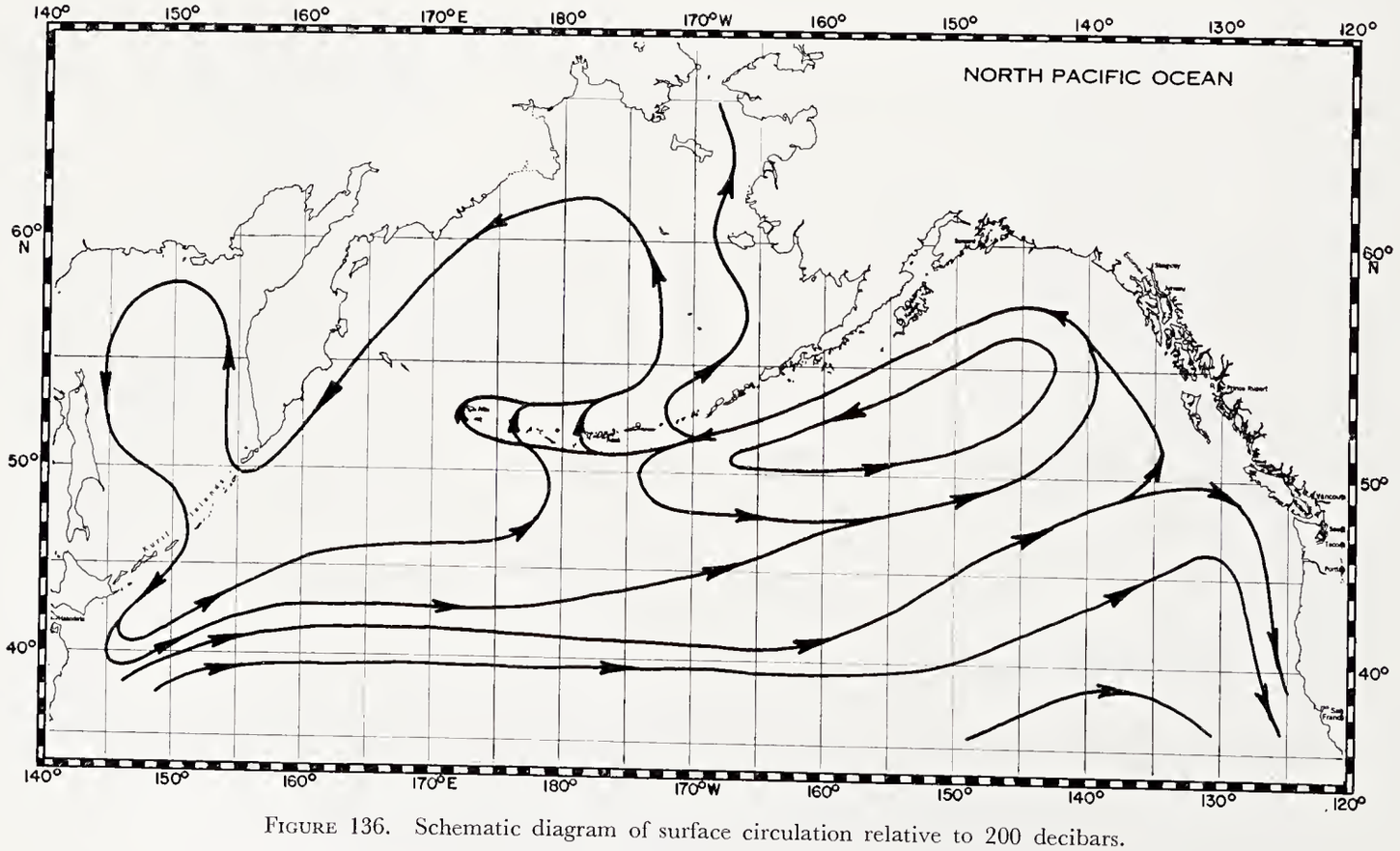


FIGURE 136. Schematic diagram of surface circulation relative to 200 decibars.

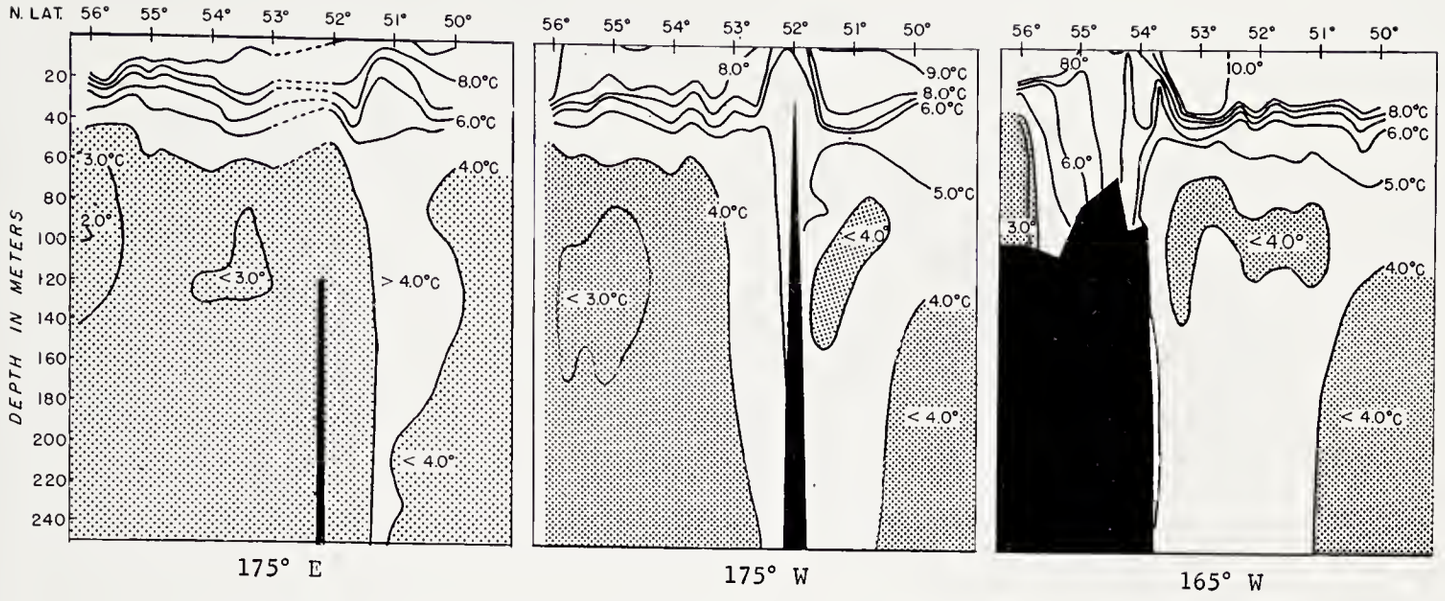


FIGURE 137a. Temperature sections across Aleutian Chain at long. 175°E., 175°W. and 165°W., July 1957. (Aleutian Chain shown in black.)

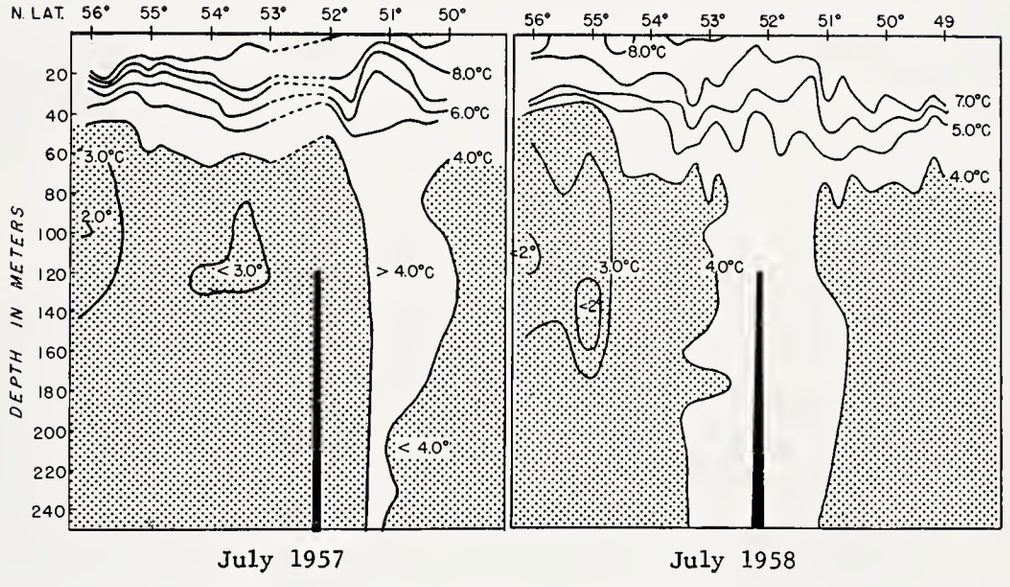
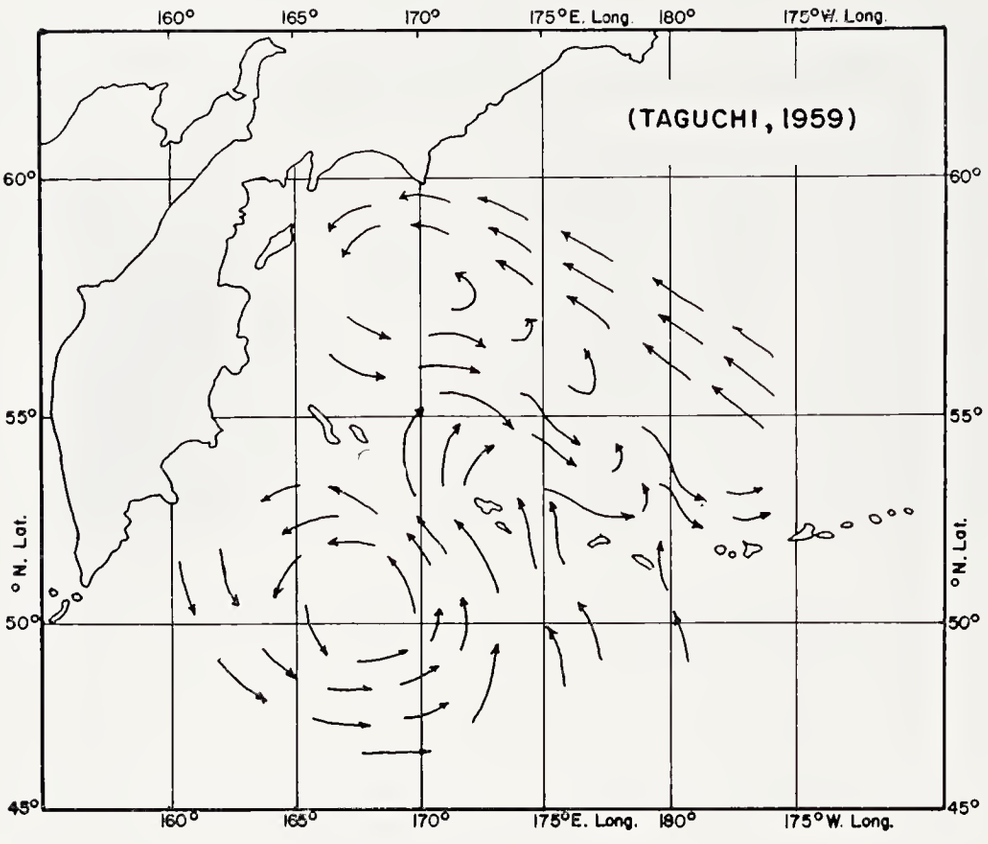


FIGURE 137b. Temperature sections across Aleutian Chain at long. 175°E., July 1957 and 1958. (Aleutian Chain shown in black.)



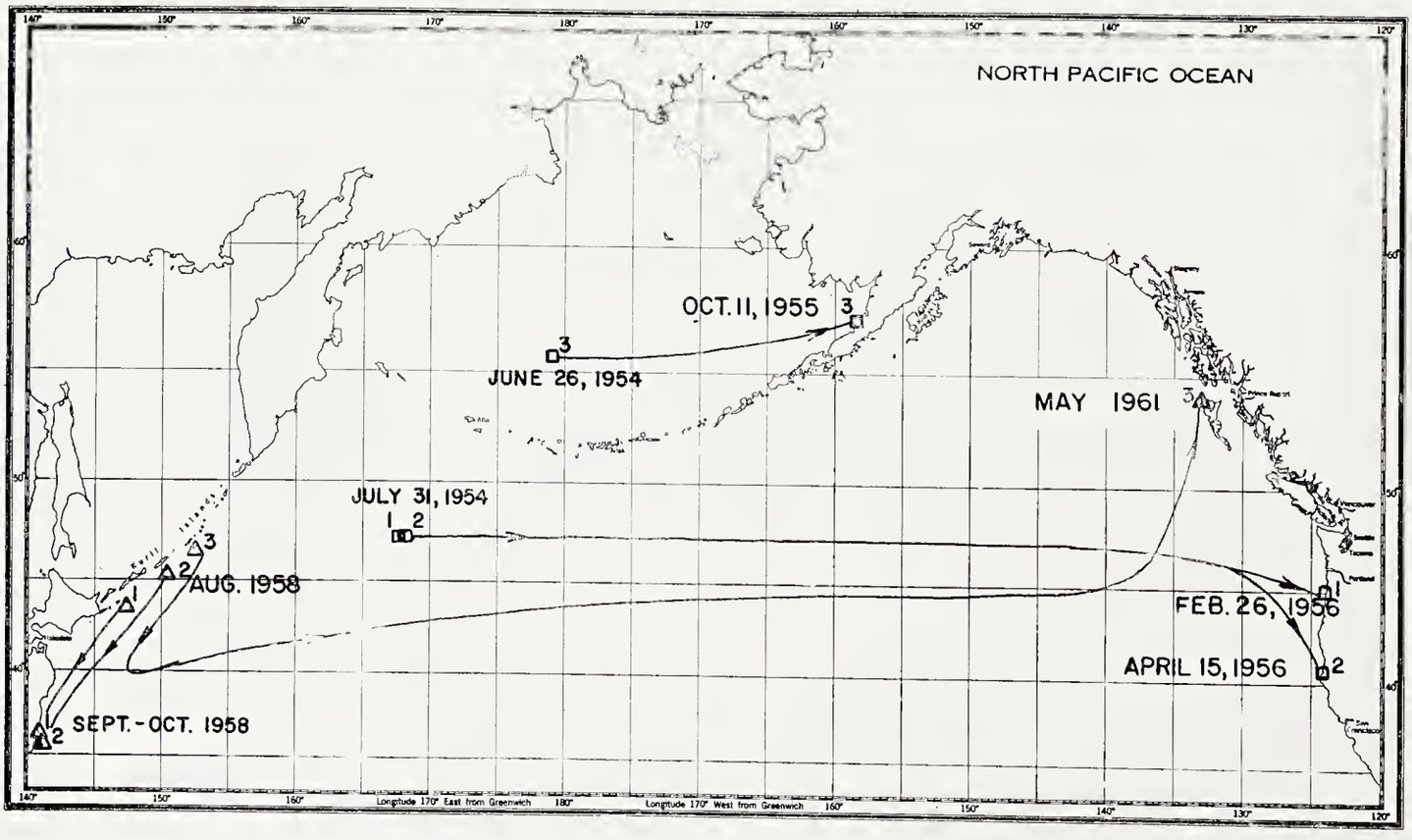
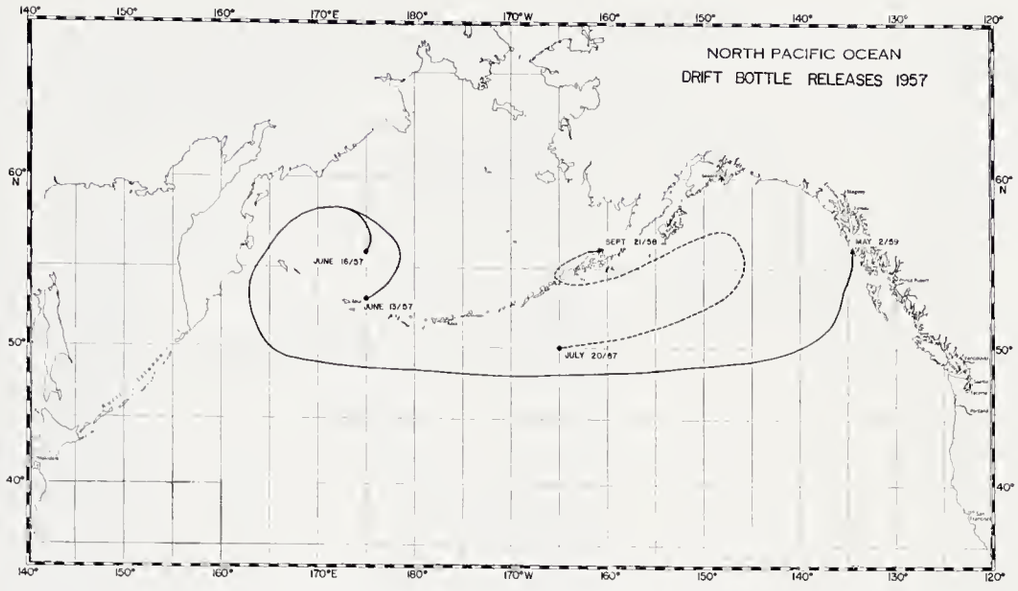
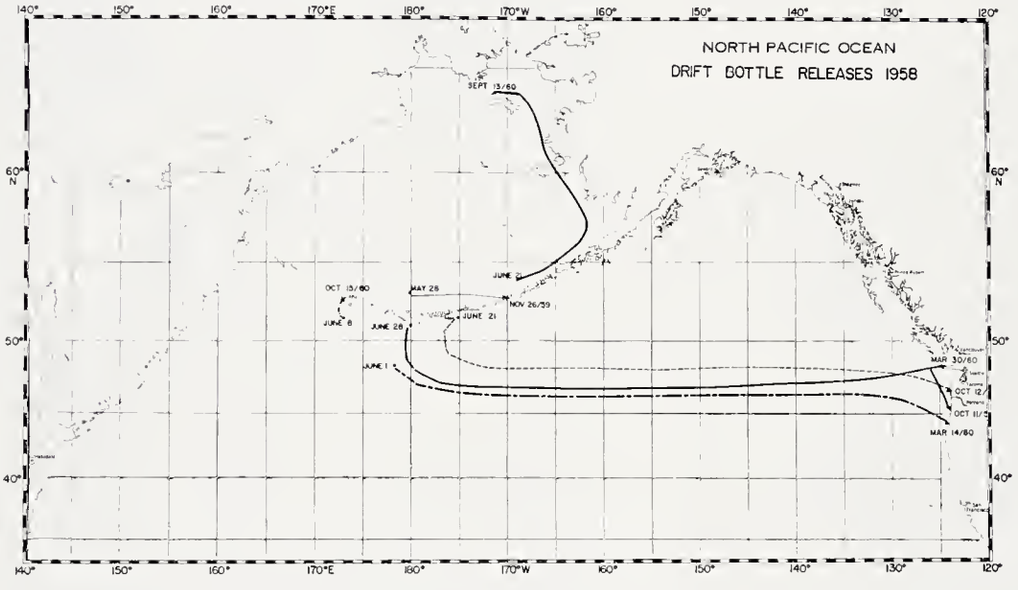


FIGURE 138. Drift bottle releases in western Subarctic.





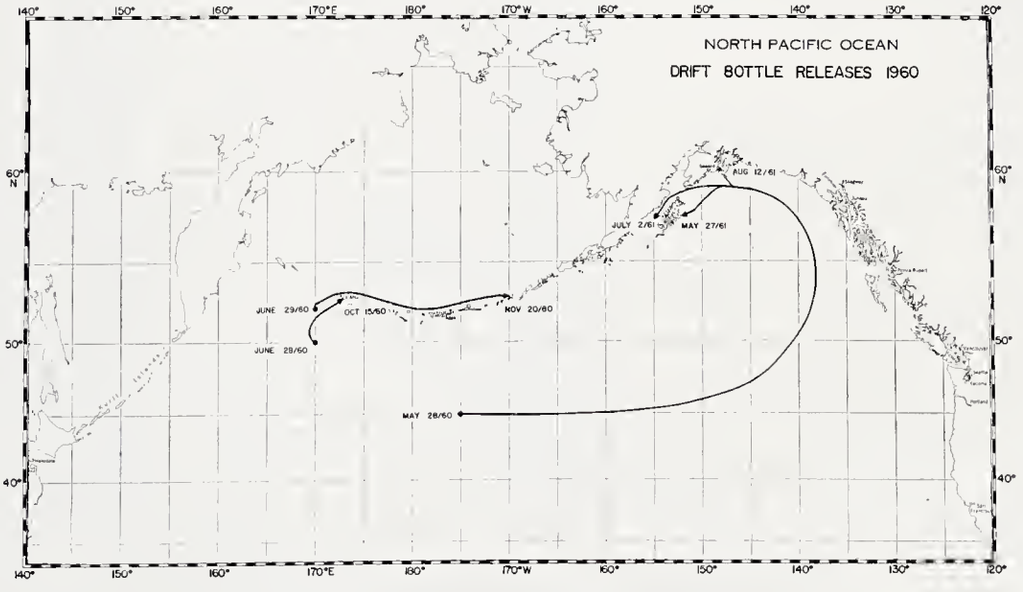
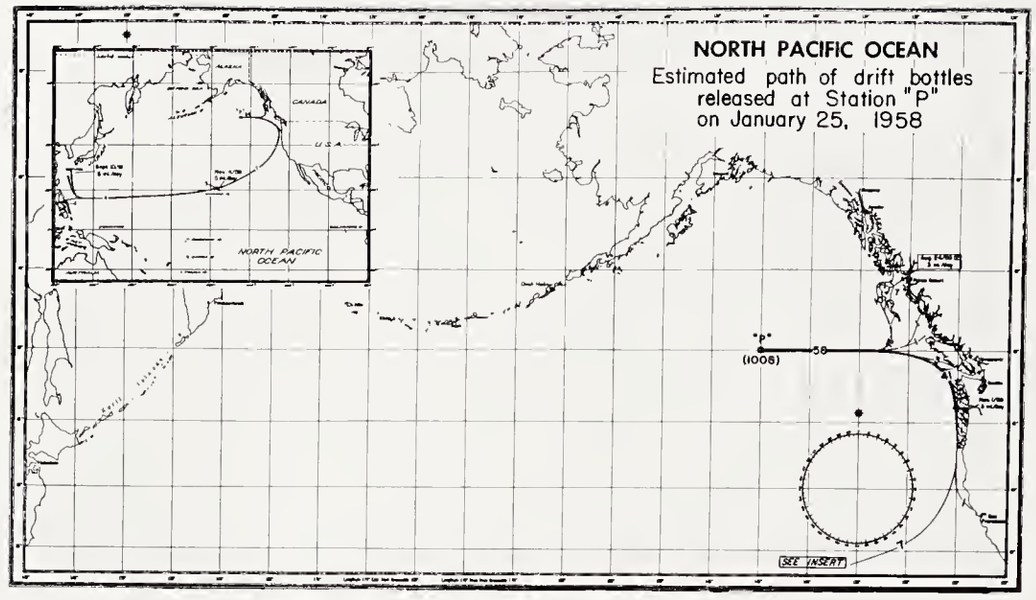
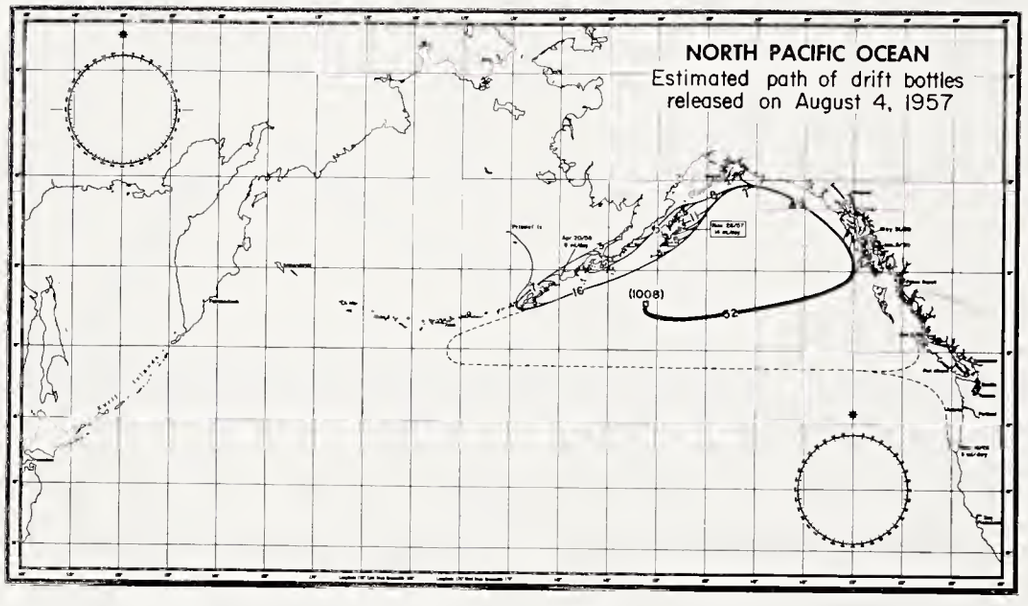


FIGURE 139. Drift bottle releases in central Subarctic.





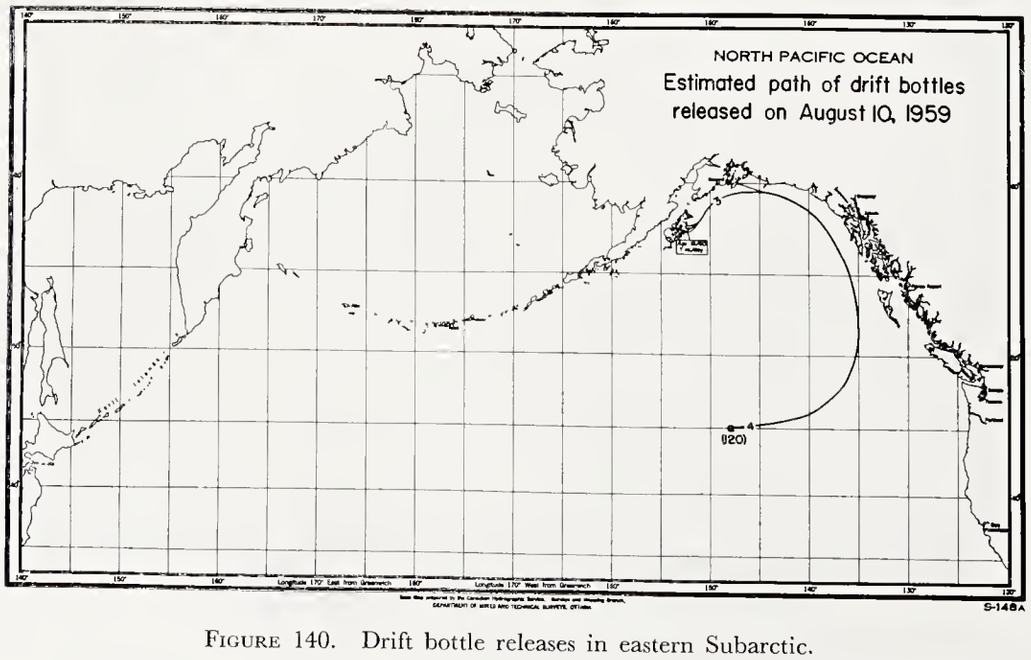


FIGURE 140. Drift bottle releases in eastern Subarctic.

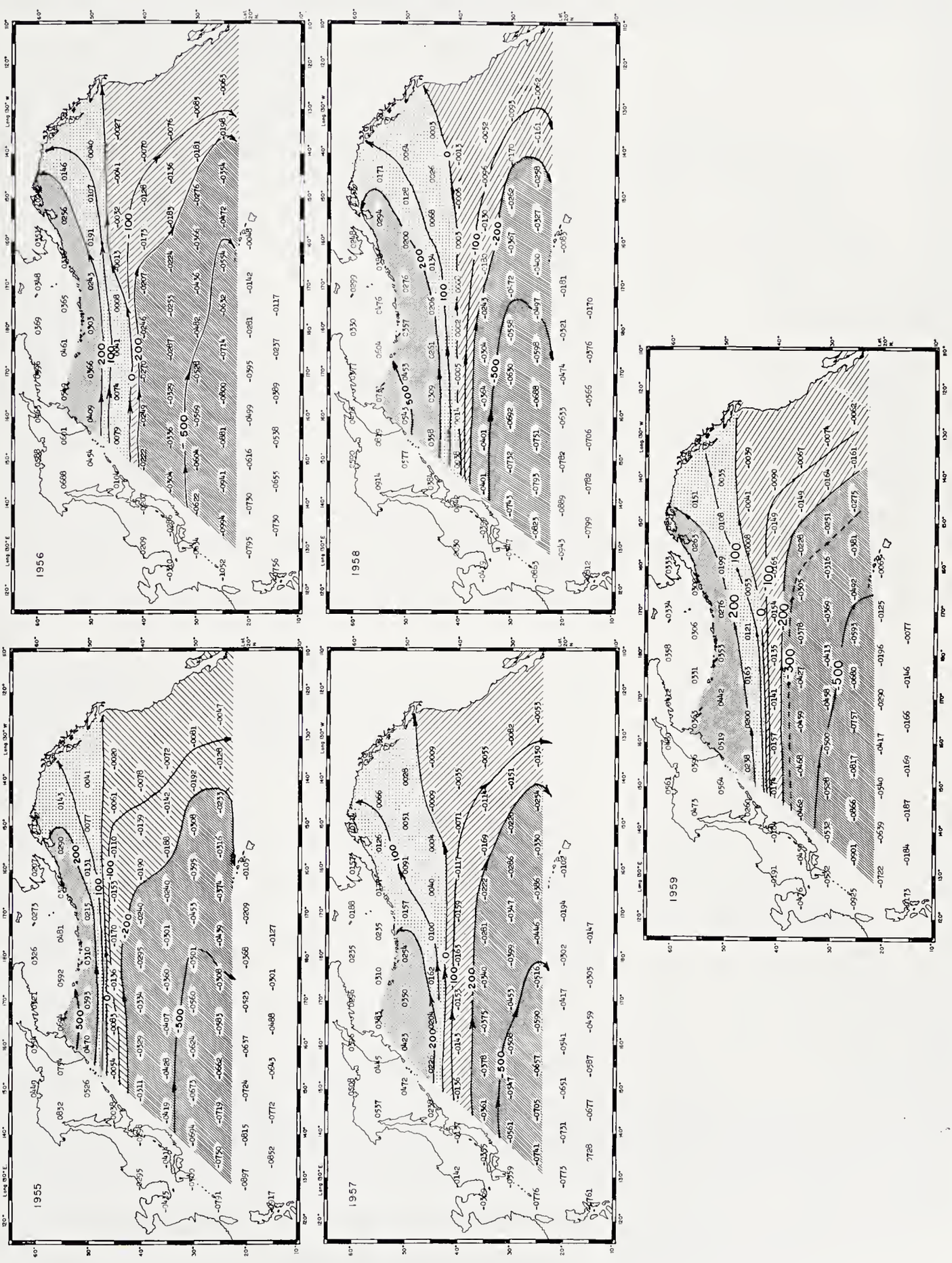
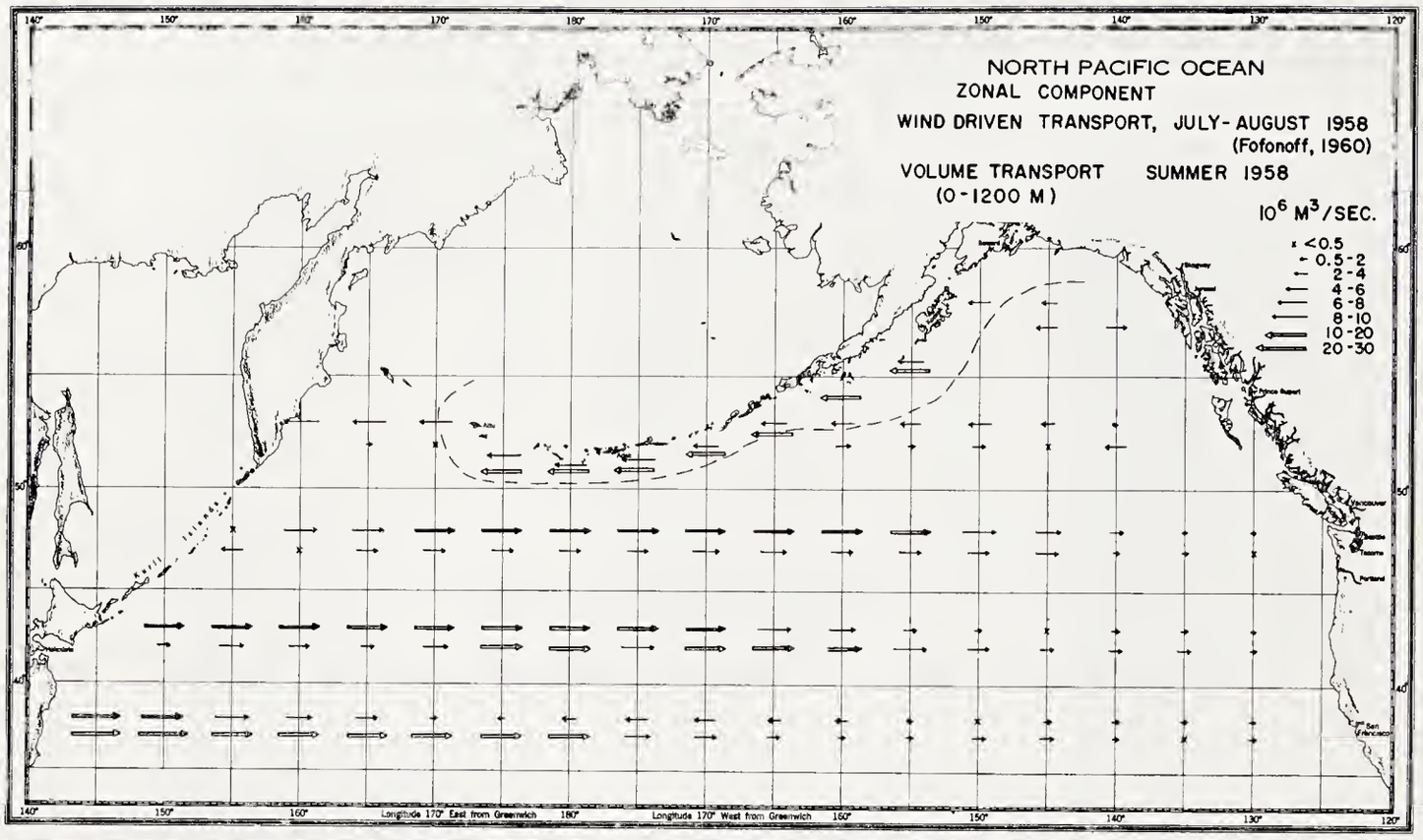


FIGURE 141. Annual mean geostrophic transports, 1955 through 1959.



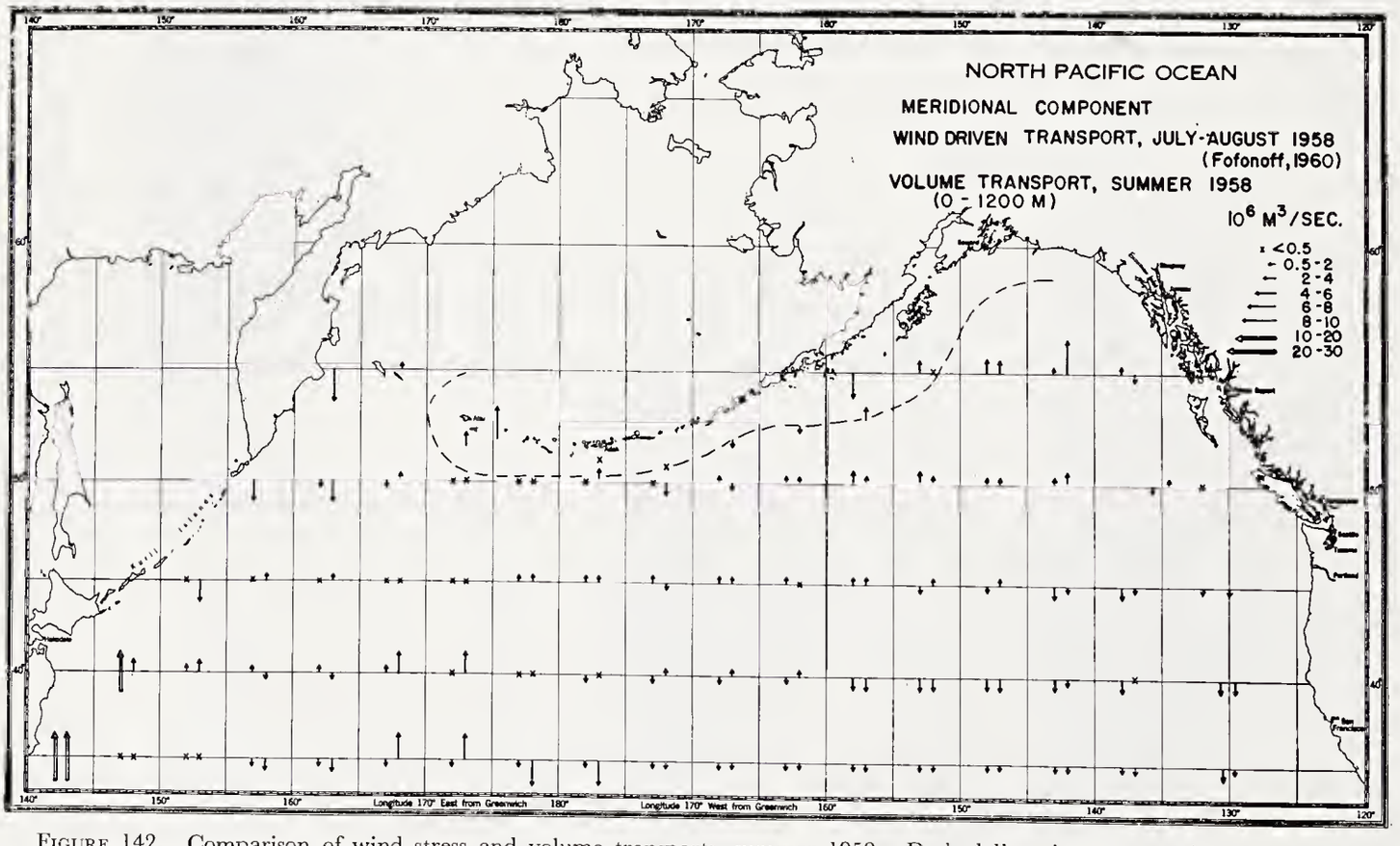


FIGURE 142. Comparison of wind stress and volume transports, summer 1958. Dashed line shows approximate extent of Alaskan Stream.

Upper: Comparison of zonal components of geostrophic mass transport computed from wind stress (upper arrow in eaeh set) and volume transport computed from hydrographic data from 0 to 1200 metres (lower arrow in each set).

Lower: Comparison of meridional components of geostrophic mass transport computed from wind stress (left arrow in each set) and volume transport computed from hydrographic data from 0 to 1200 metres (right arrow in each set).

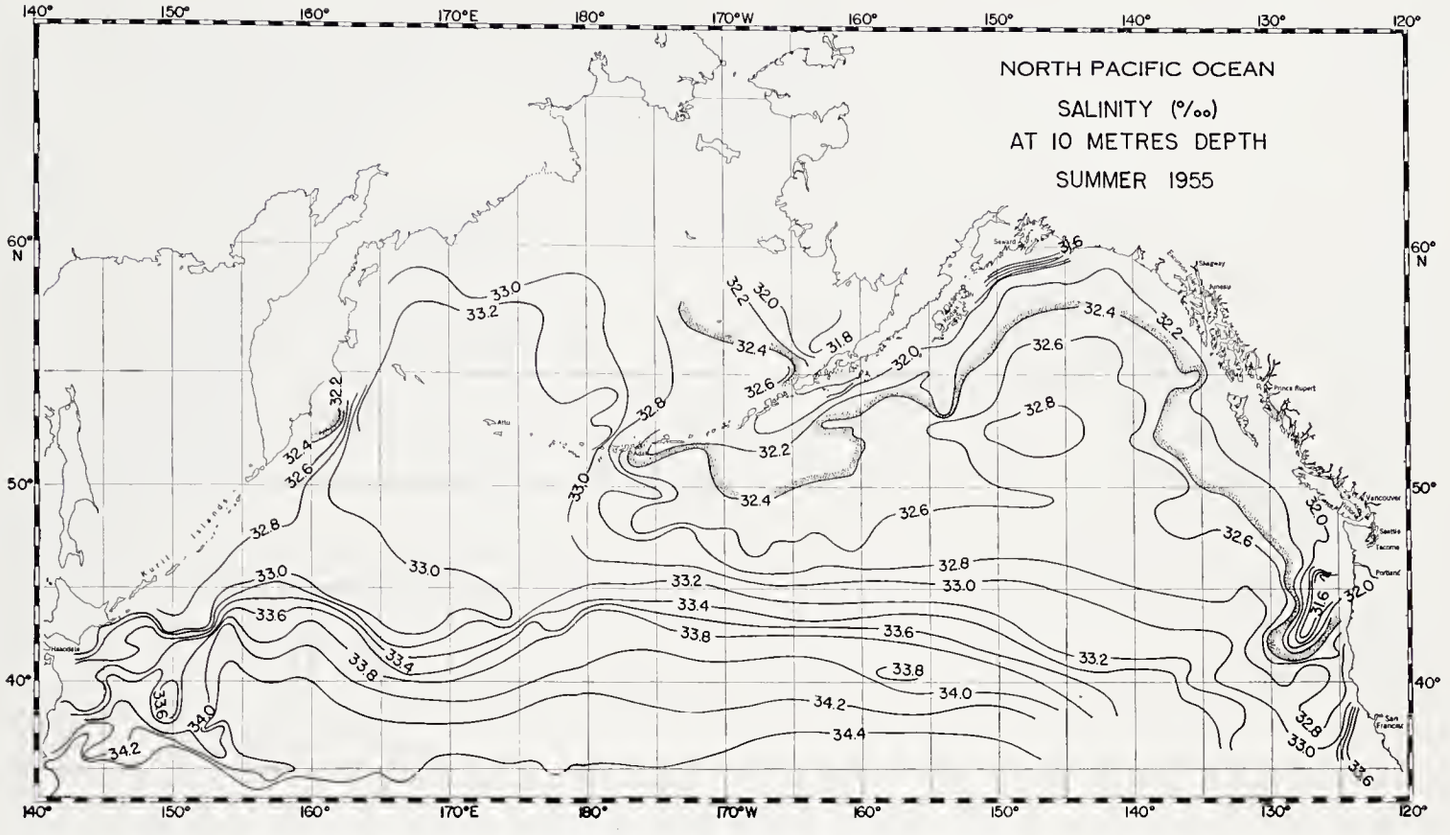


FIGURE 143. Salinity at 10 metres depth, summer 1955.

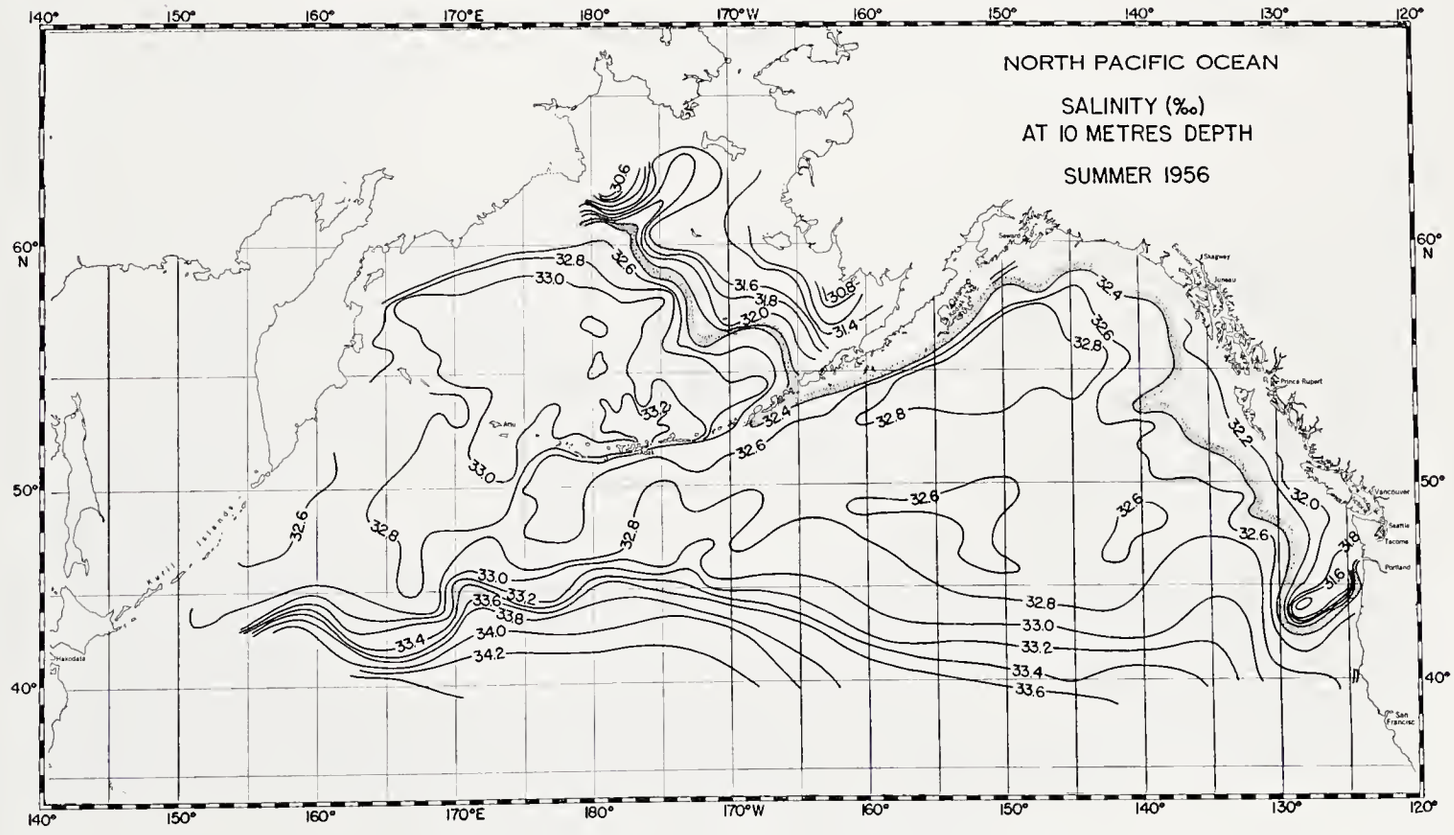


FIGURE 144. Salinity at 10 metres depth, summer 1956.

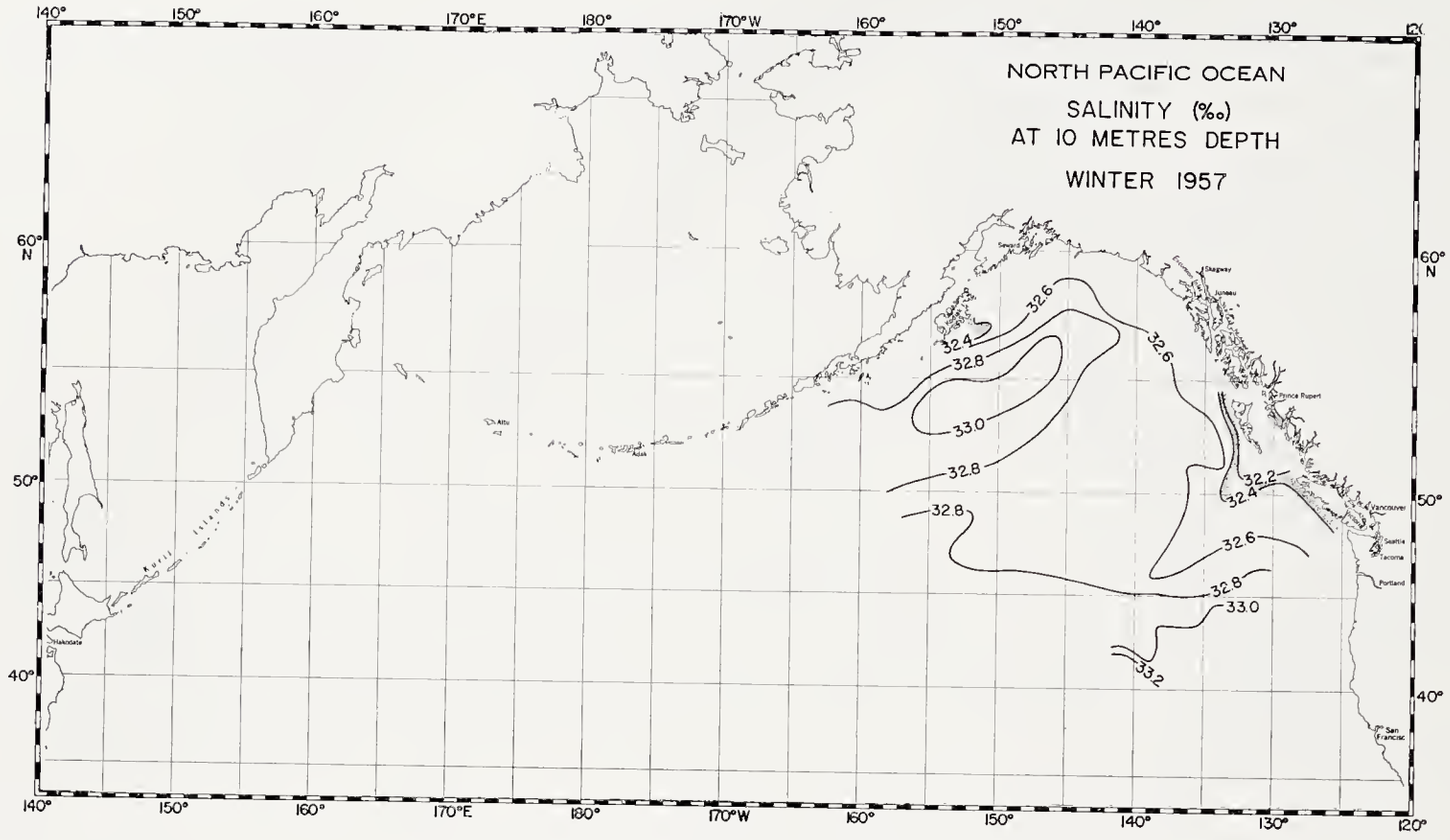


FIGURE 145. Salinity at 10 metres depth, winter 1957.

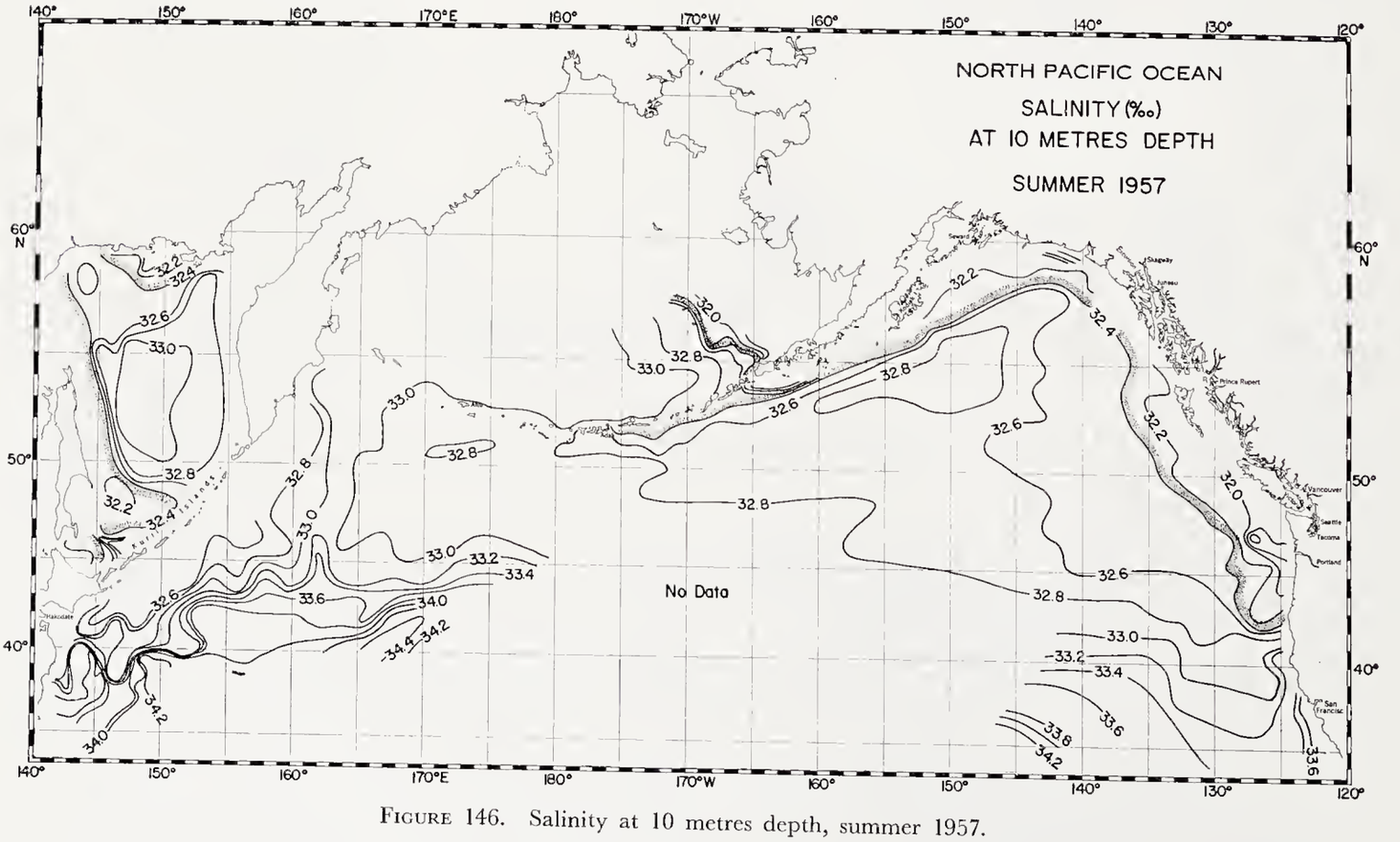


FIGURE 146. Salinity at 10 metres depth, summer 1957.

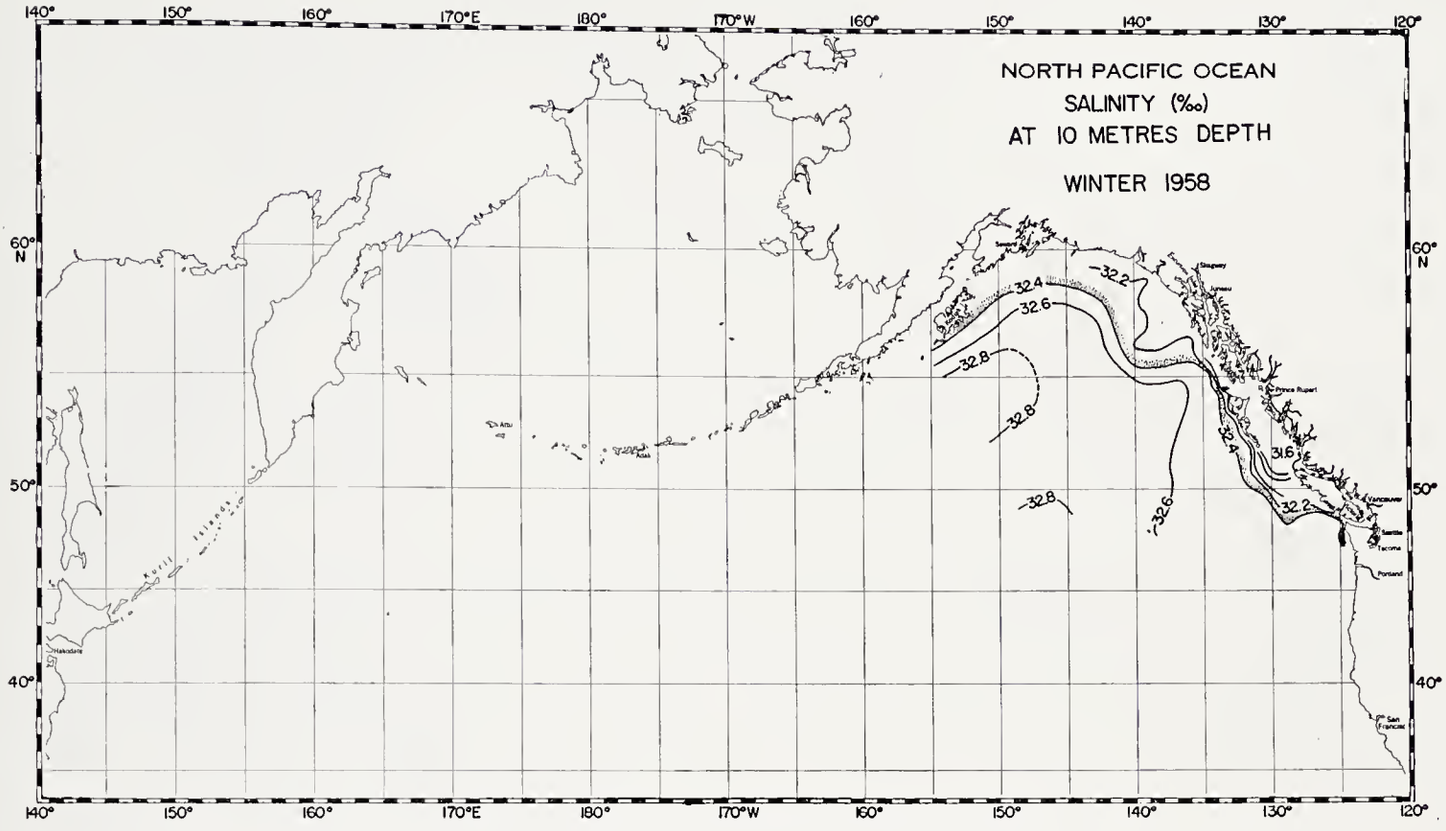


FIGURE 147. Salinity at 10 metres depth, winter 1958.

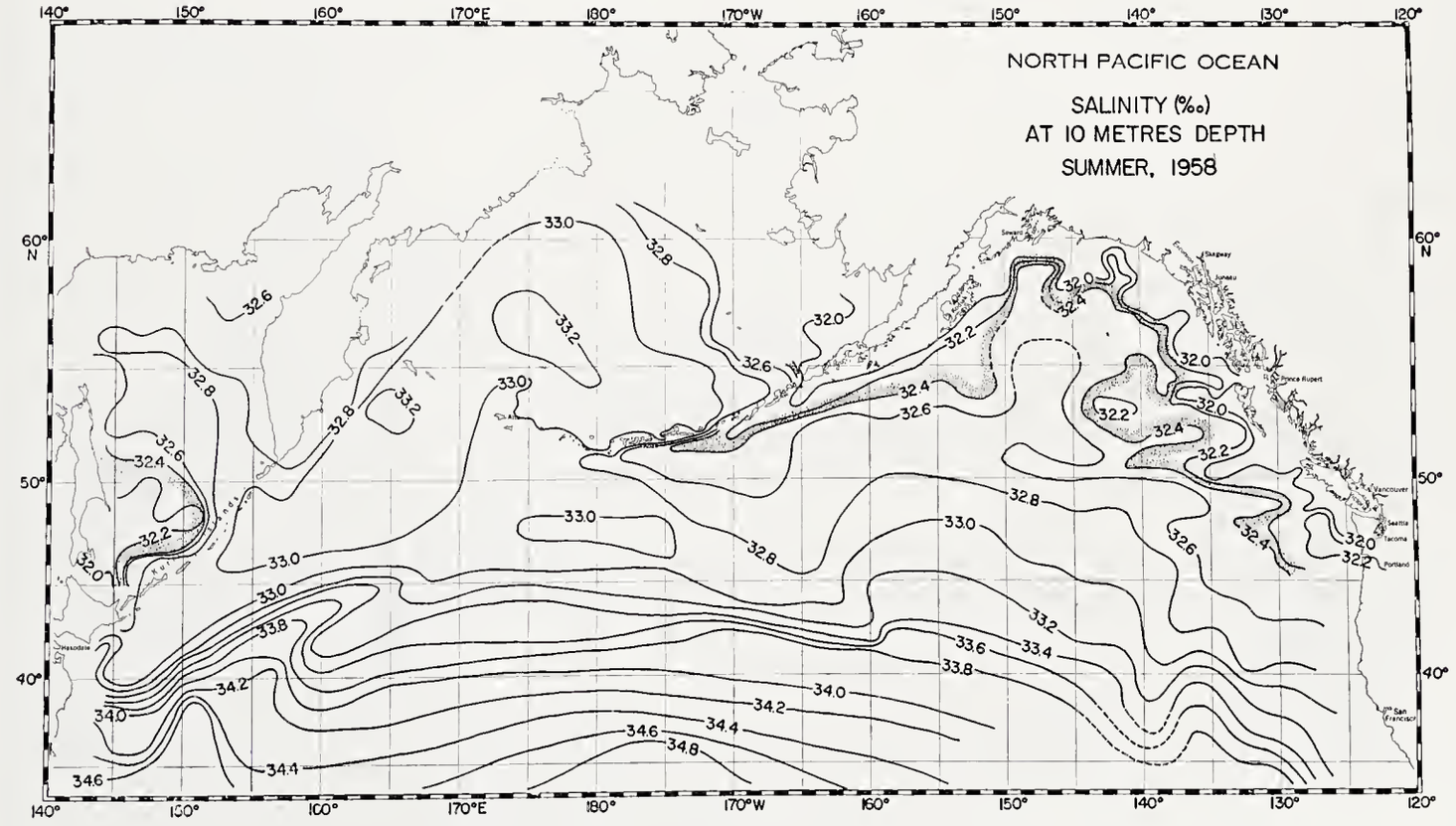


FIGURE 148. Salinity at 10 metres depth, summer 1958.

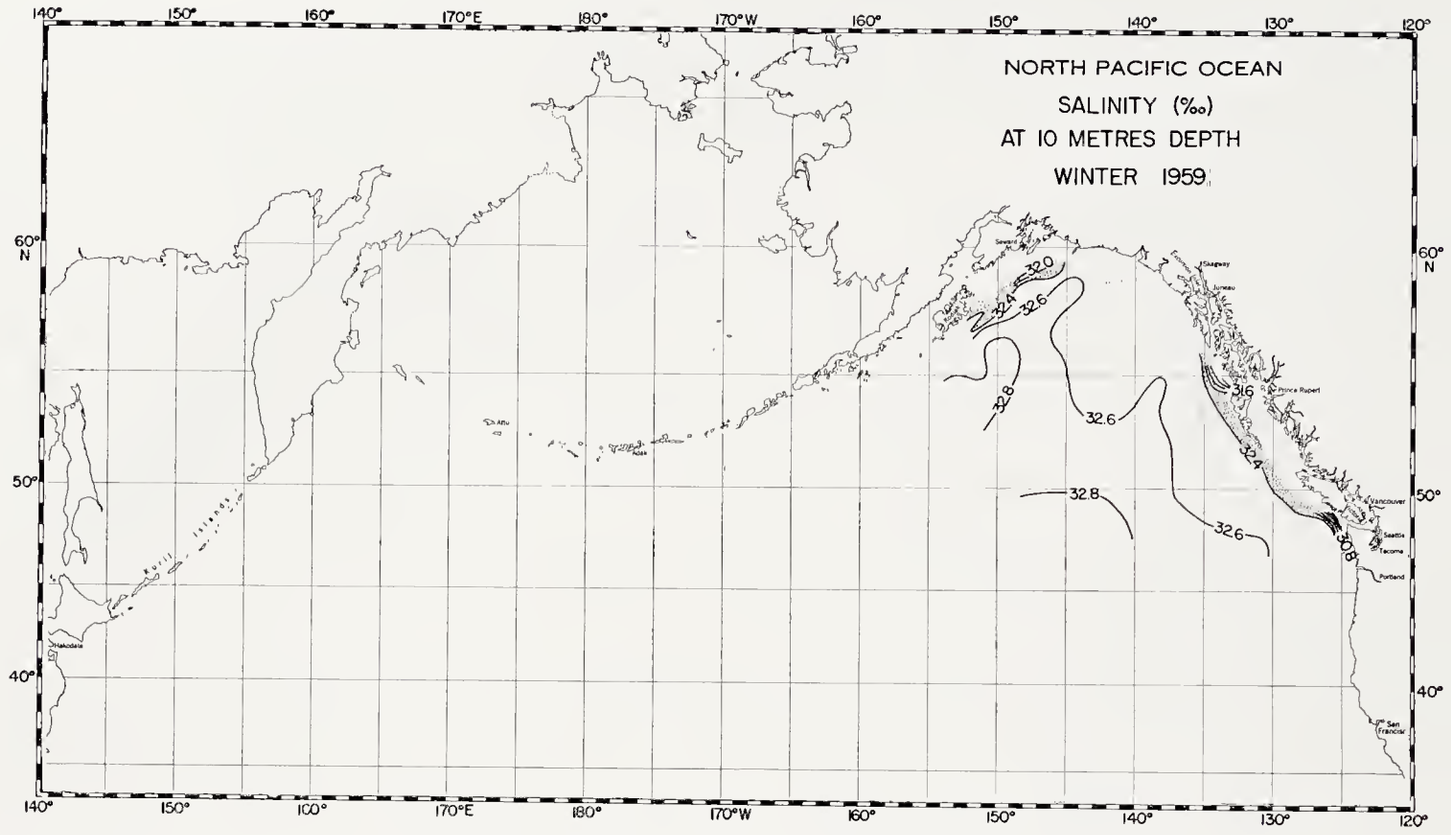


FIGURE 149. Salinity at 10 metres depth, winter 1959.

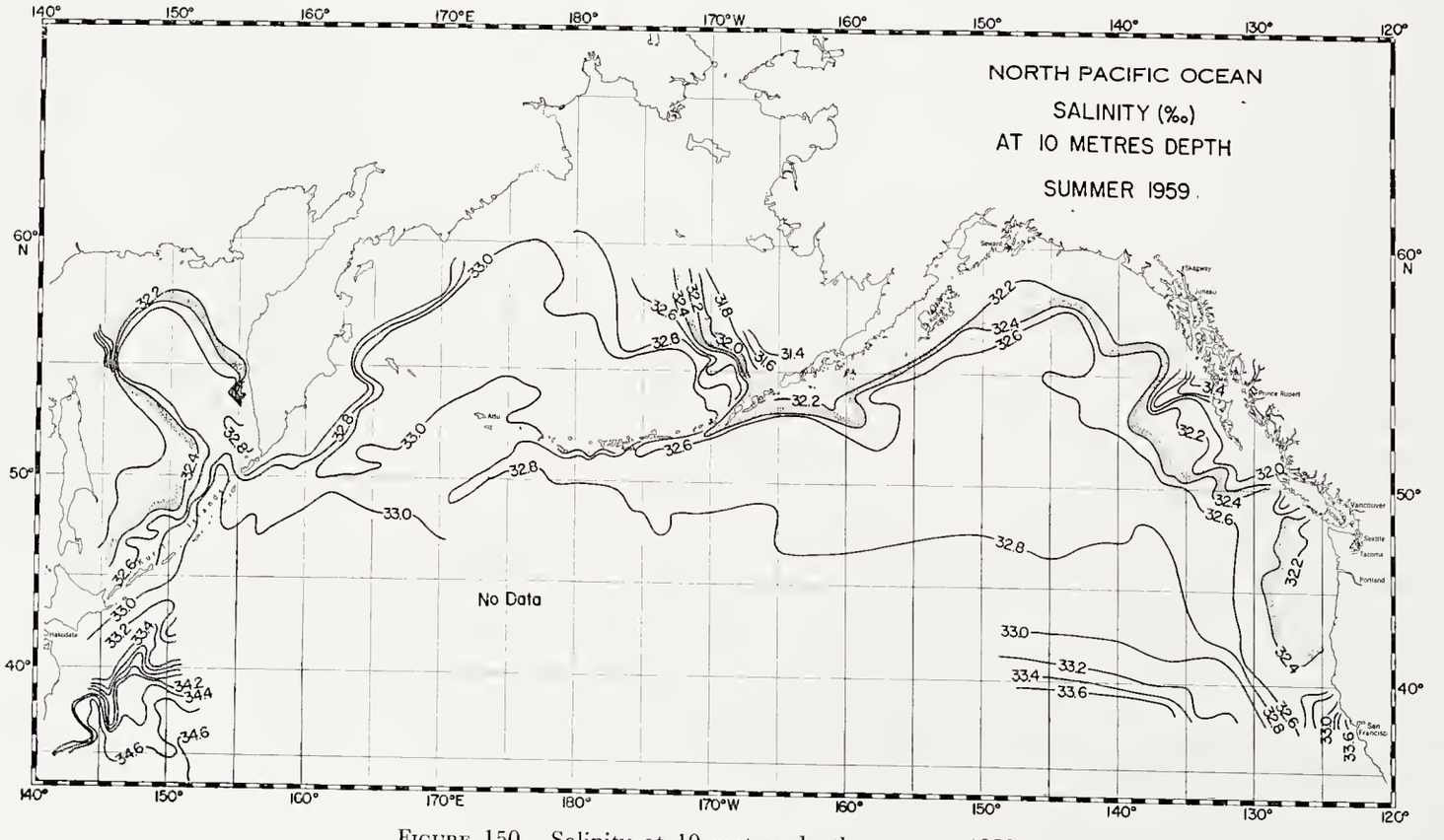


FIGURE 150. Salinity at 10 metres depth, summer 1959.

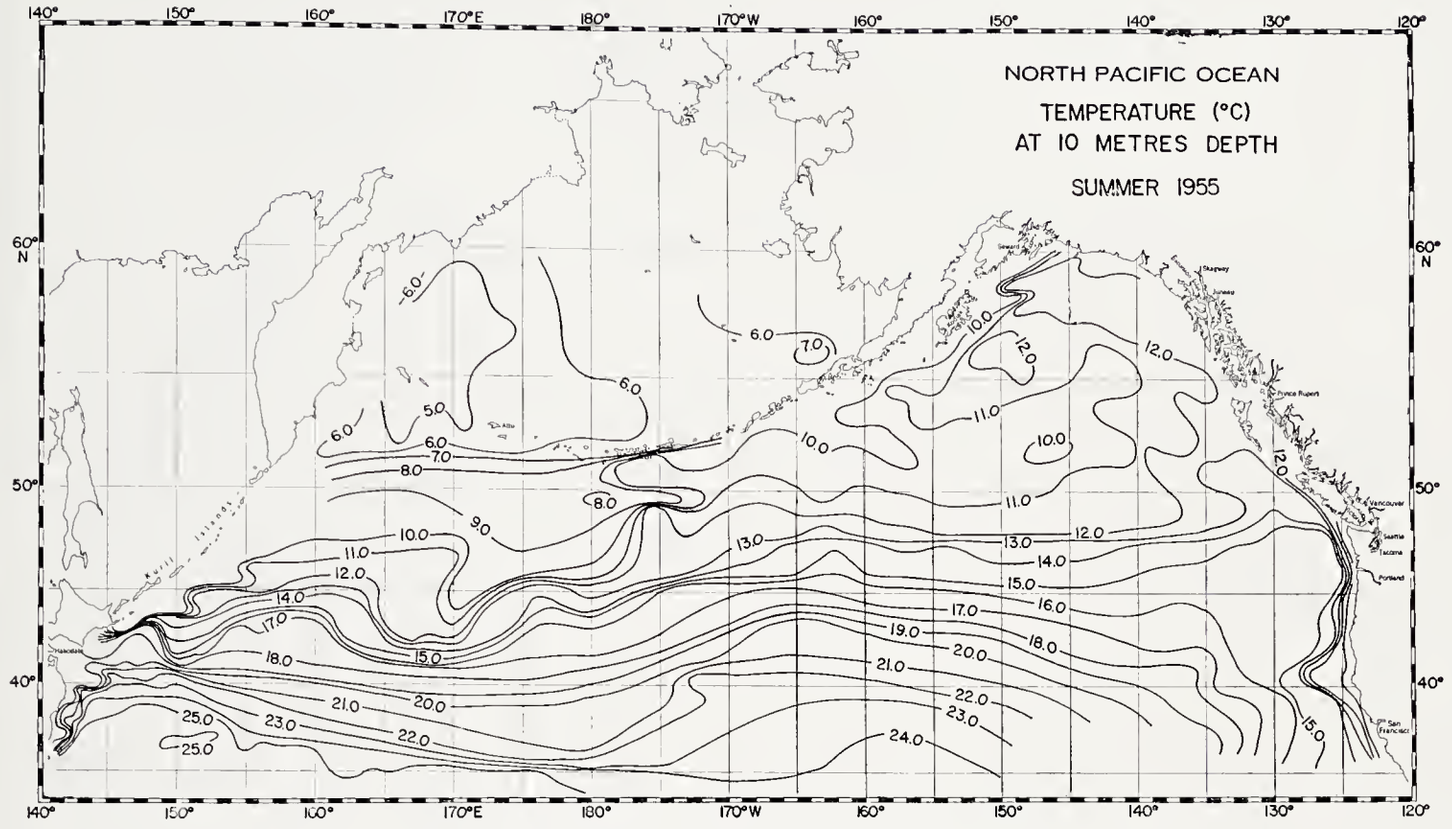


FIGURE 151. Temperature at 10 metres depth, summer 1955.

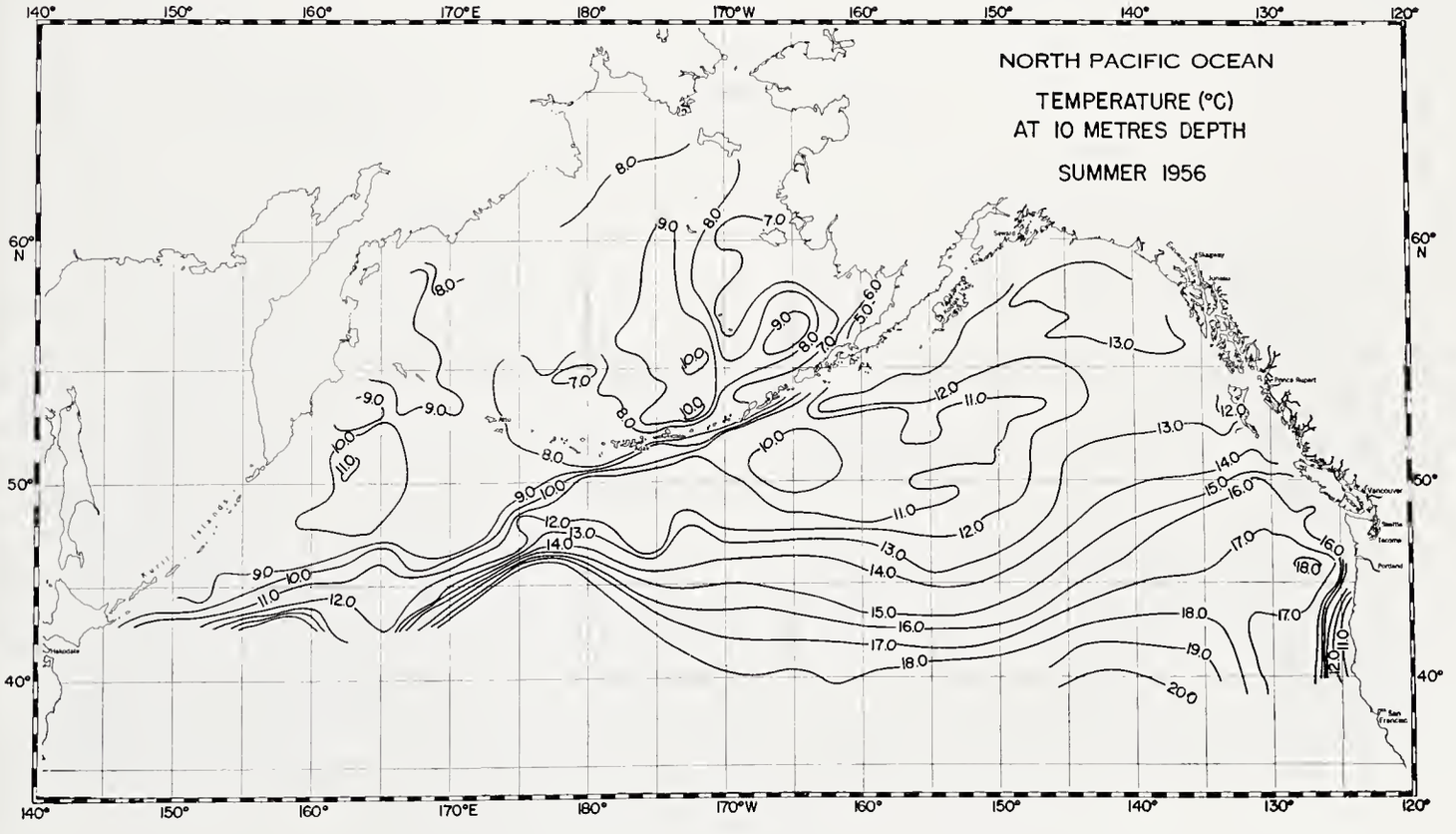


FIGURE 152. Temperature at 10 metres depth, summer 1956.

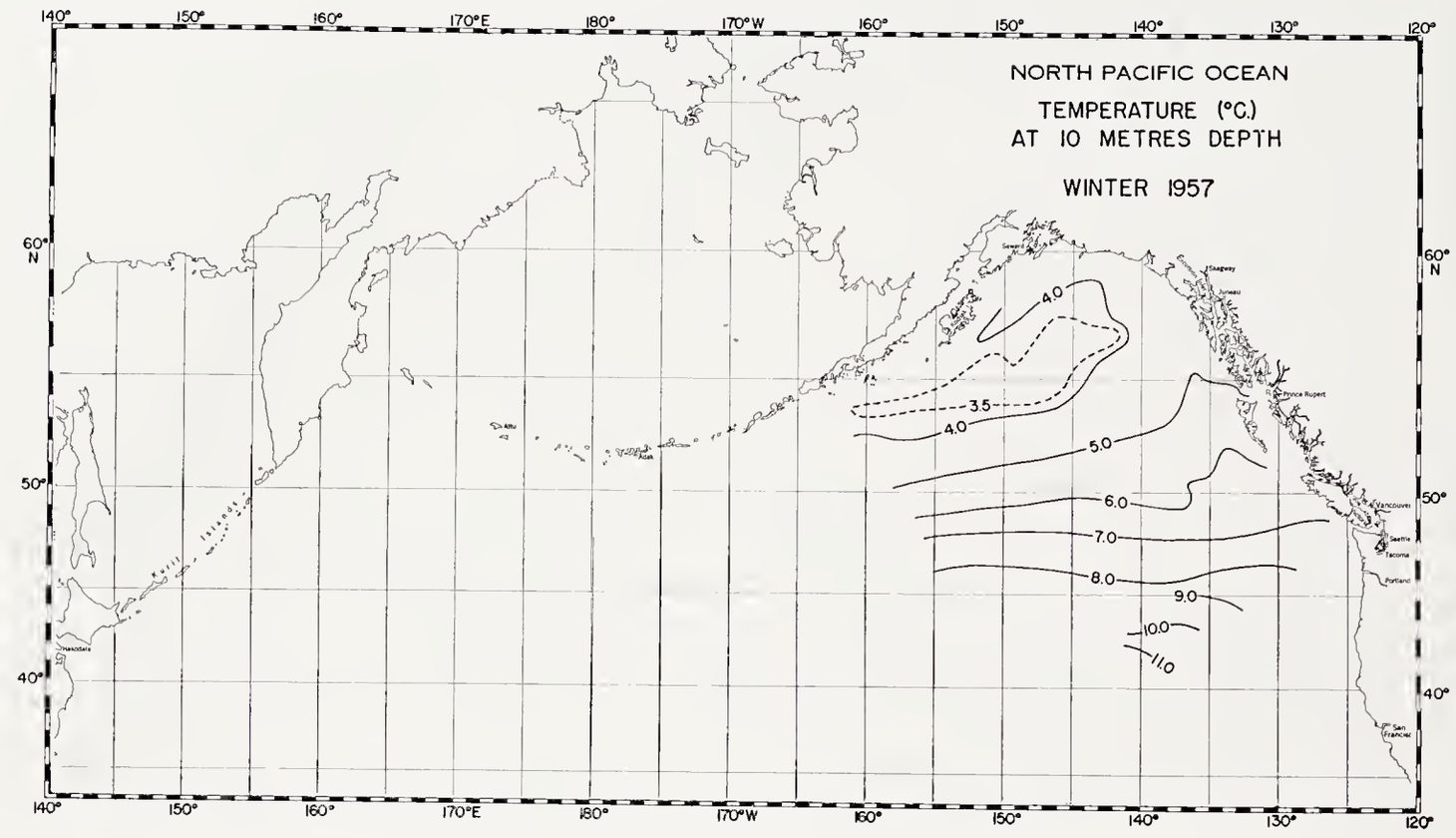


FIGURE 153. Temperature at 10 metres depth, winter 1957.

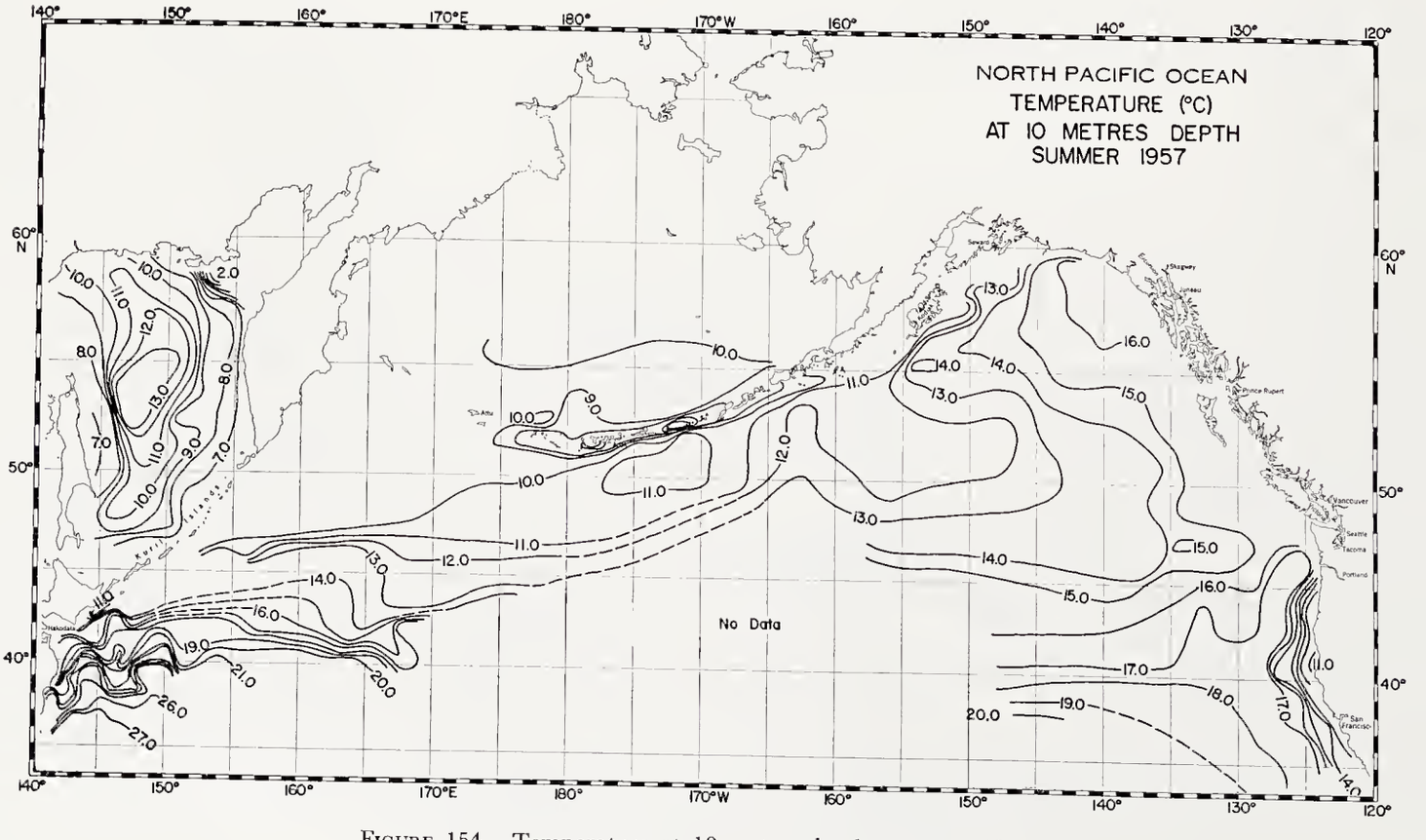


FIGURE 154. Temperature at 10 metres depth, summer 1957.

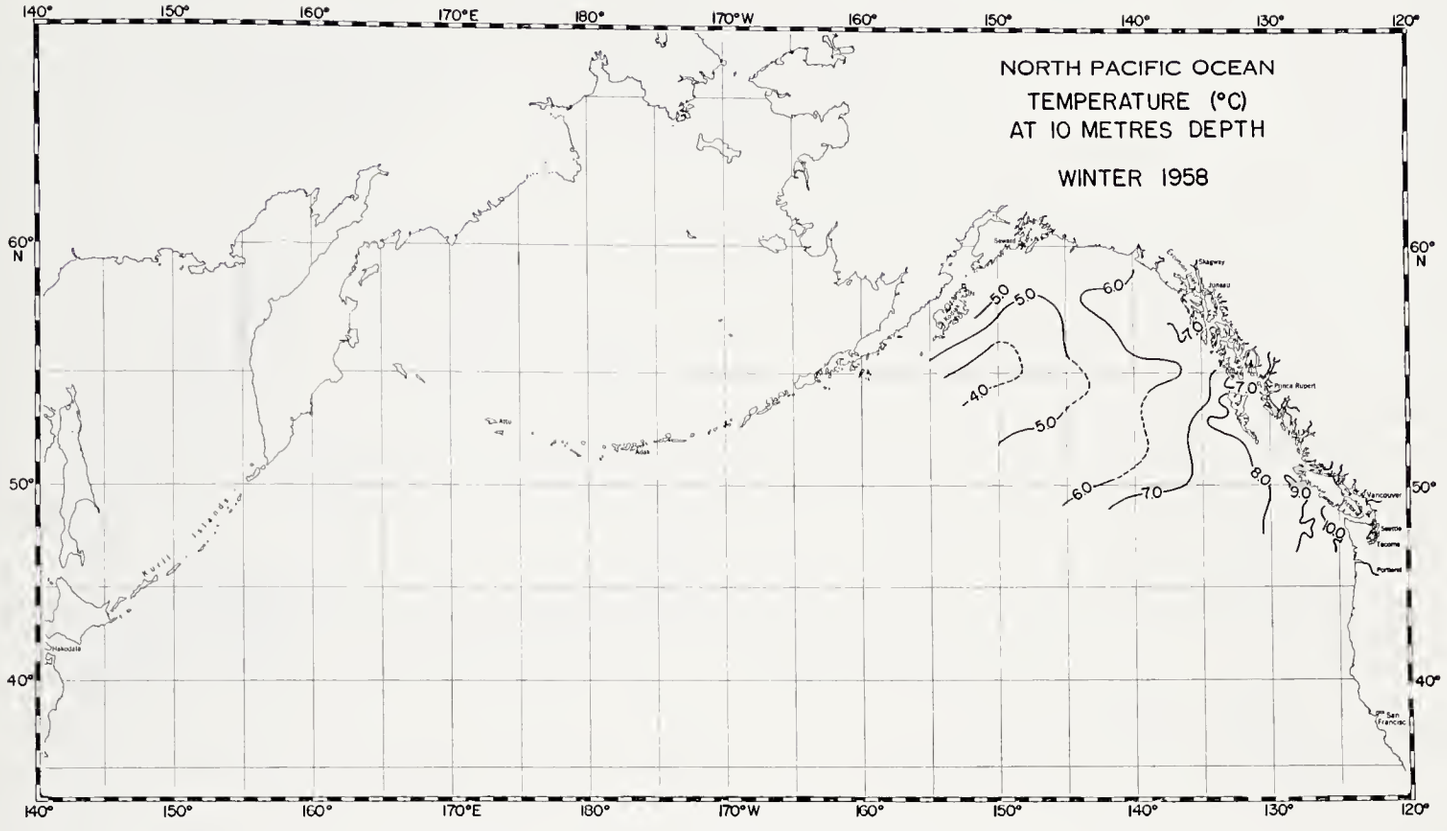


FIGURE 155. Temperature at 10 metres depth, winter 1958.

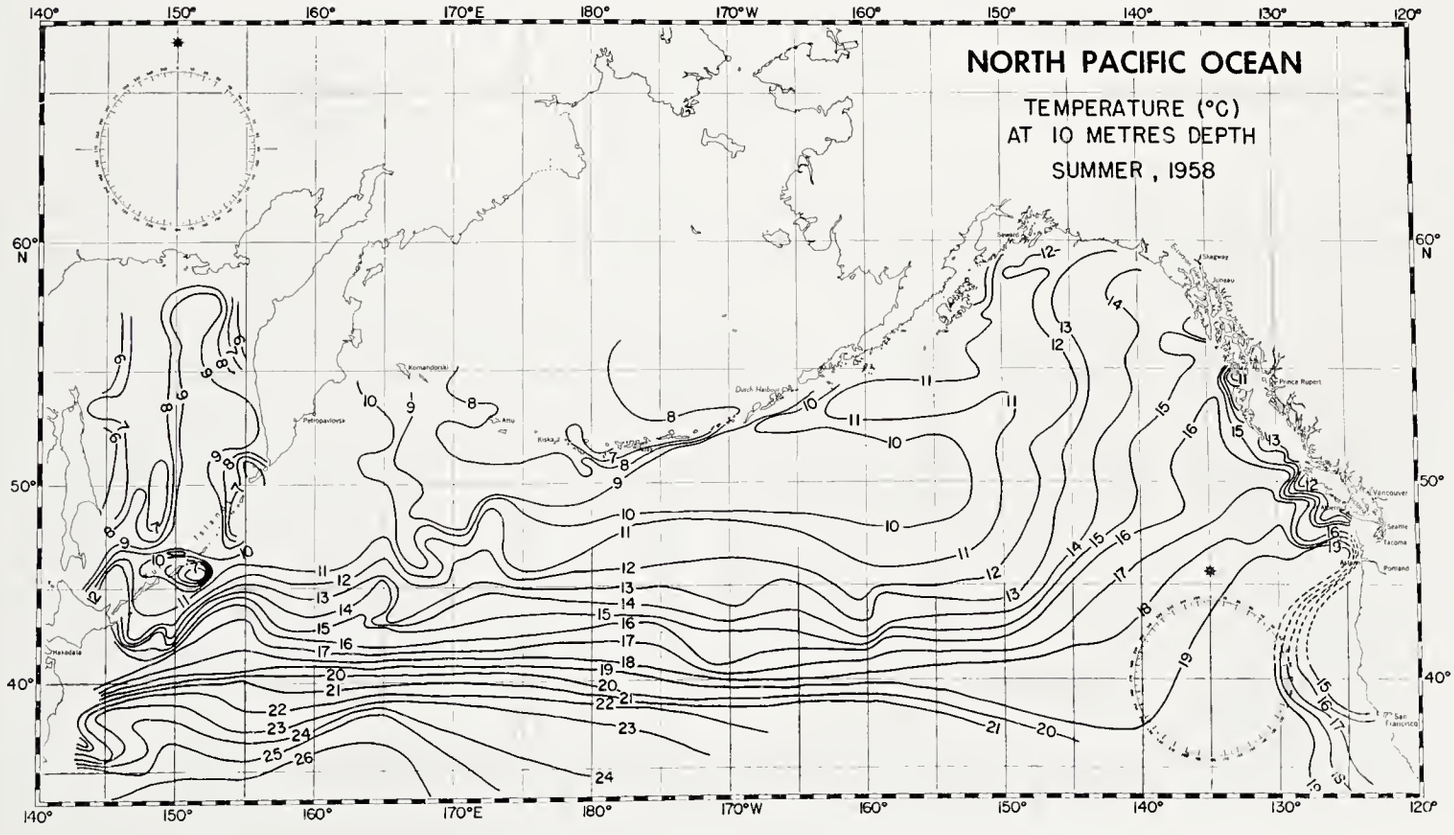


FIGURE 156. Temperature at 10 metres depth, summer 1958.

FIGURE 157. Temperature at 10 metres depth, winter 1959.

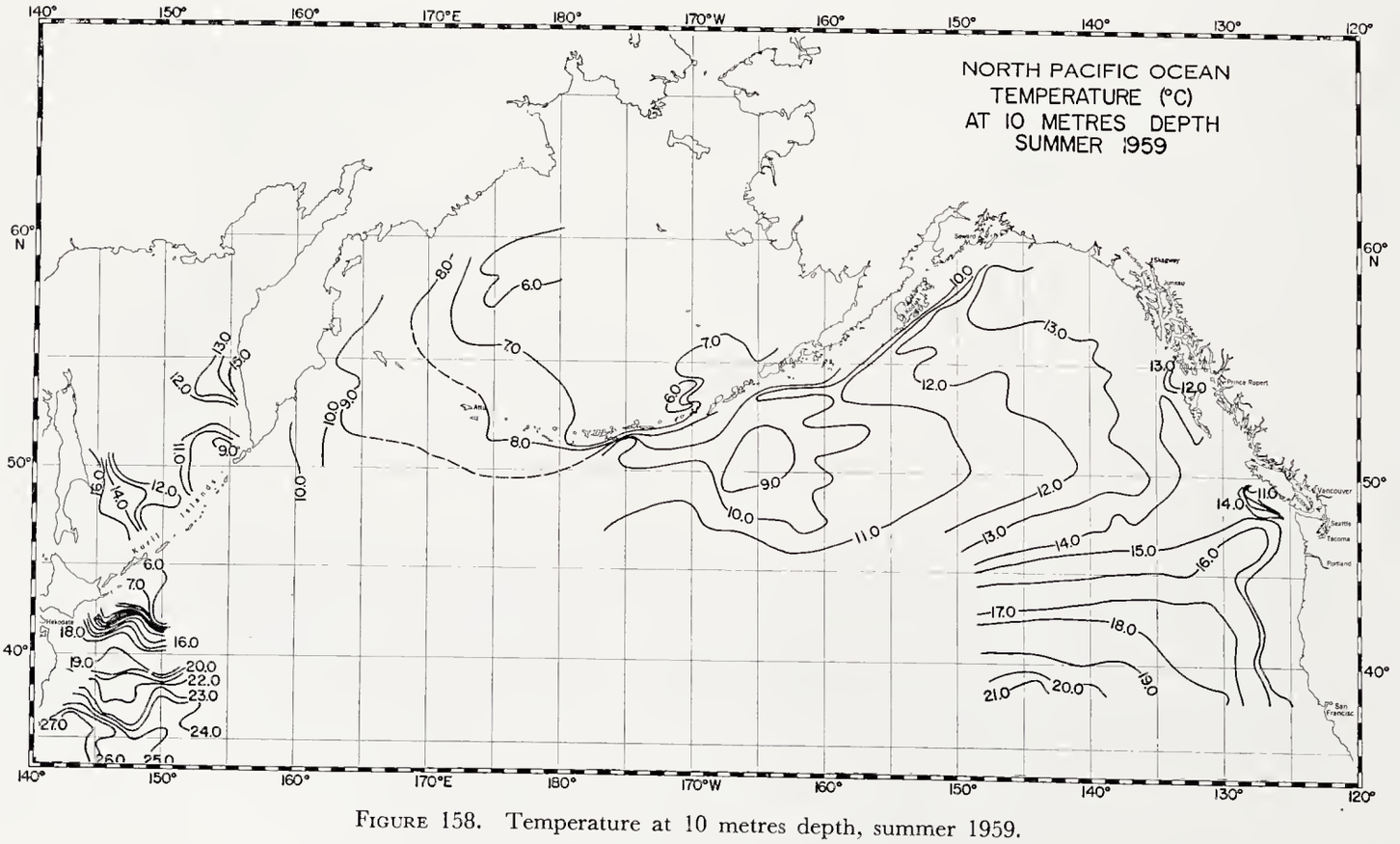


FIGURE 158. Temperature at 10 metres depth, summer 1959.

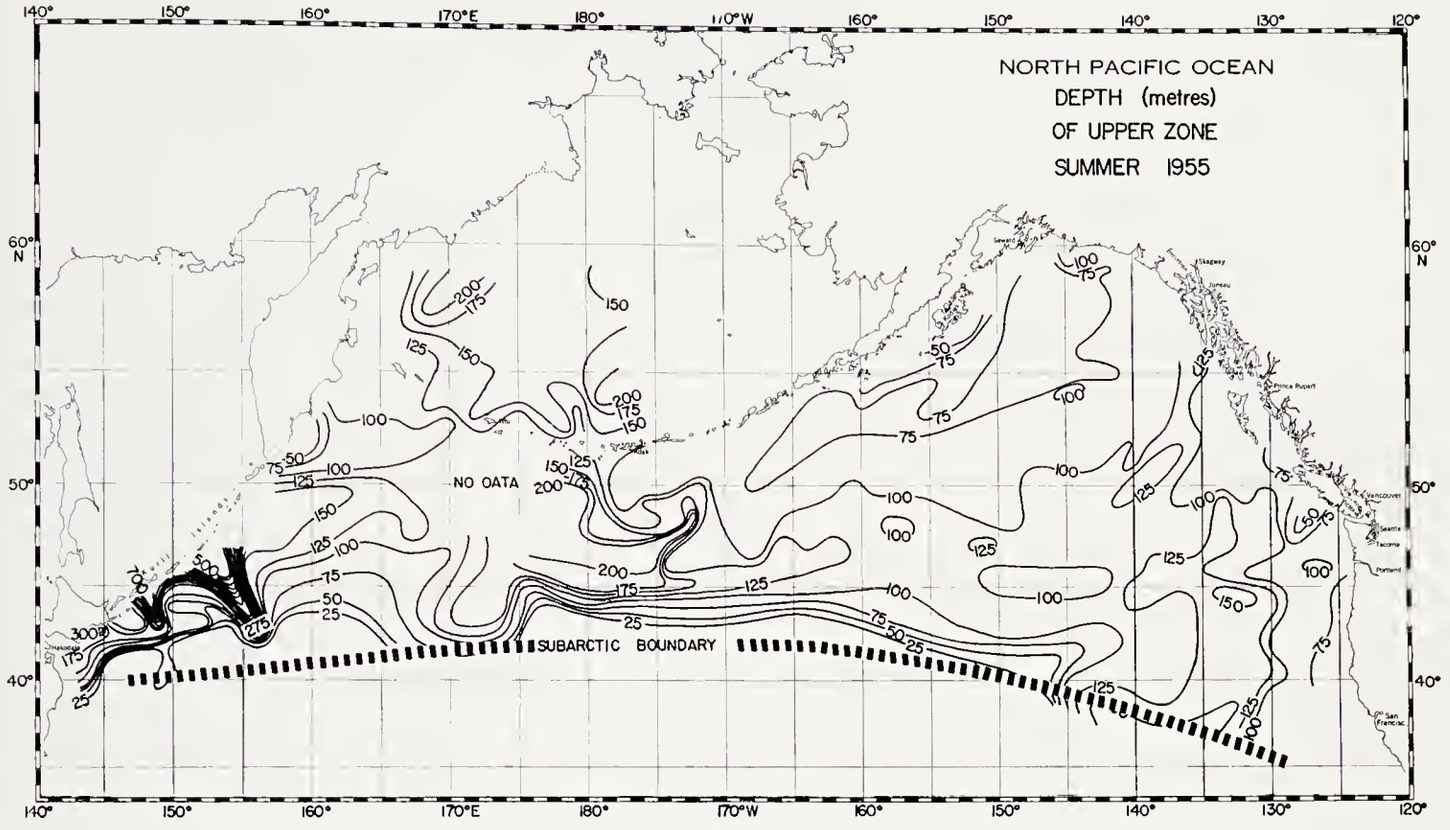


FIGURE 159. Depth (metres) of upper zone, summer 1955.

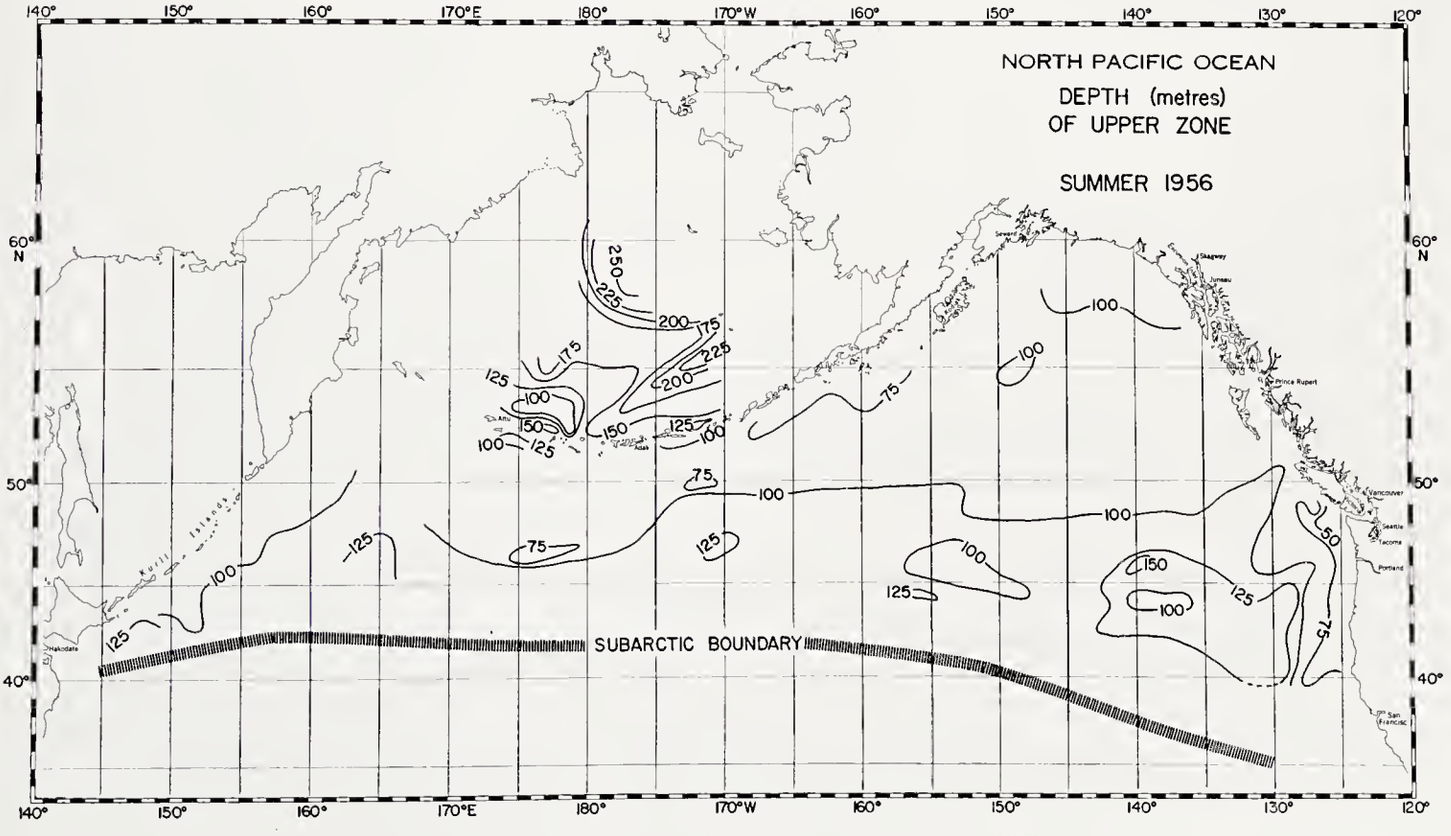


FIGURE 160. Depth (metres) of upper zone, summer 1956.

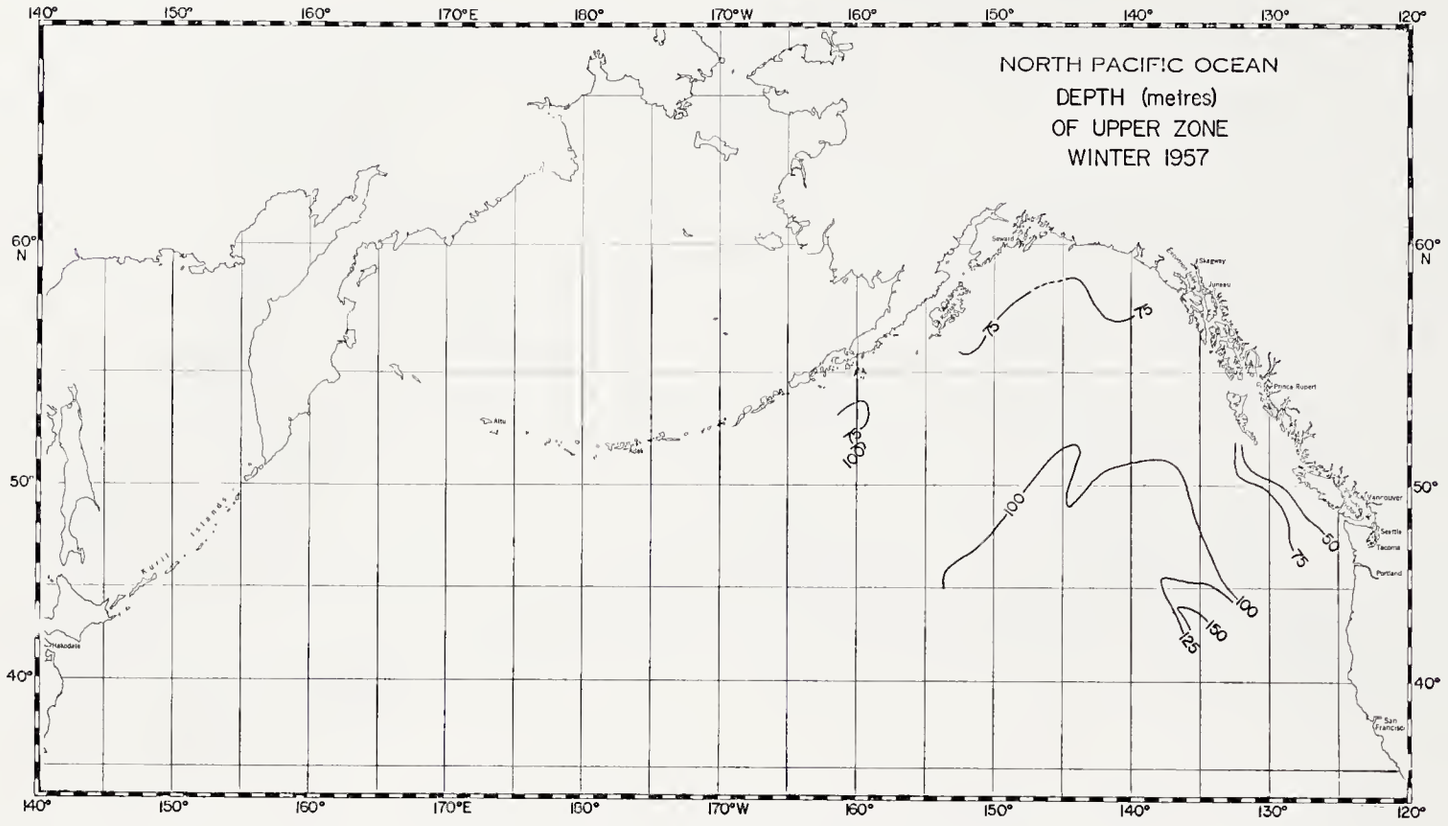


FIGURE 161. Depth (metres) of upper zone, winter 1957.

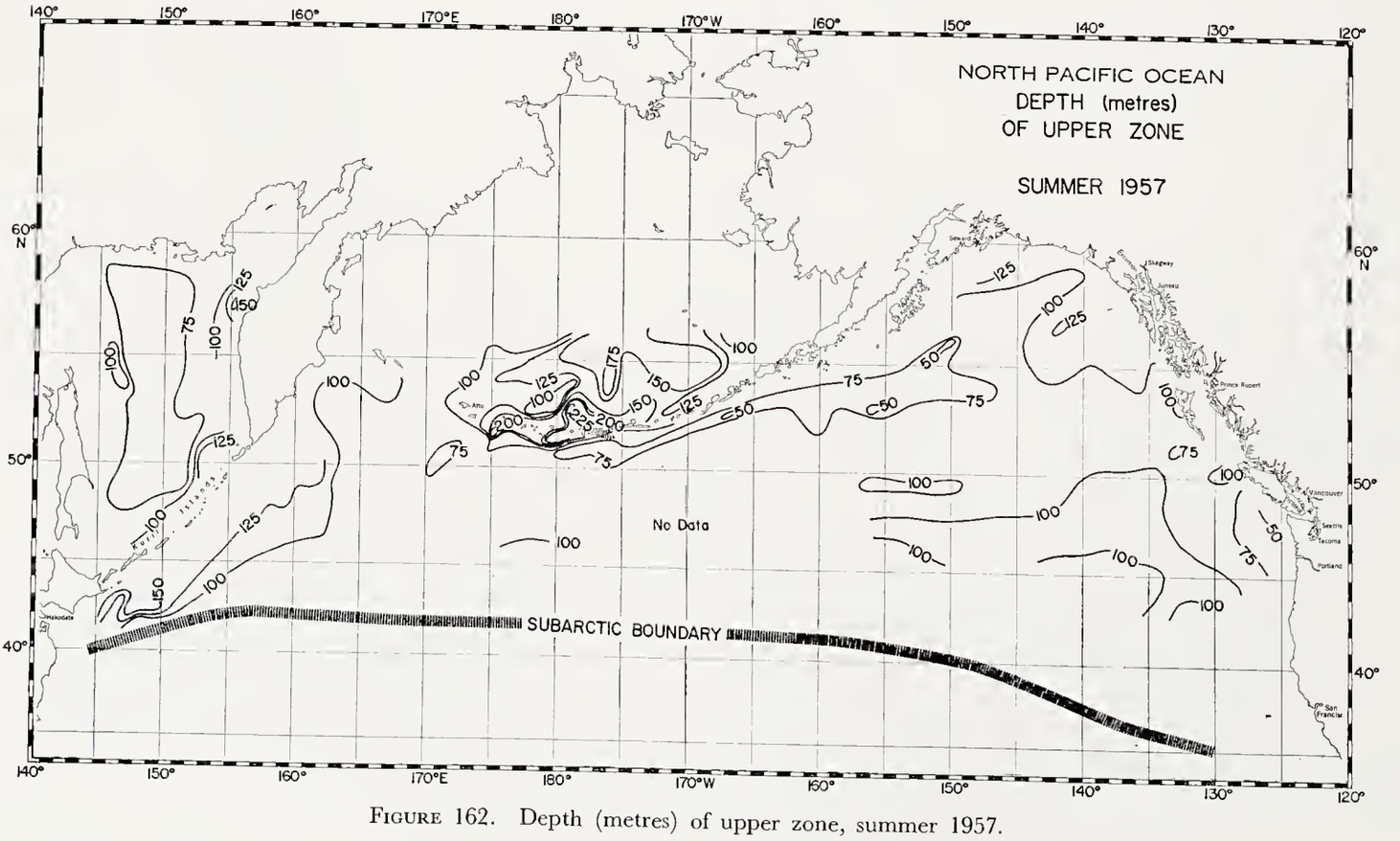


FIGURE 162. Depth (metres) of upper zone, summer 1957.

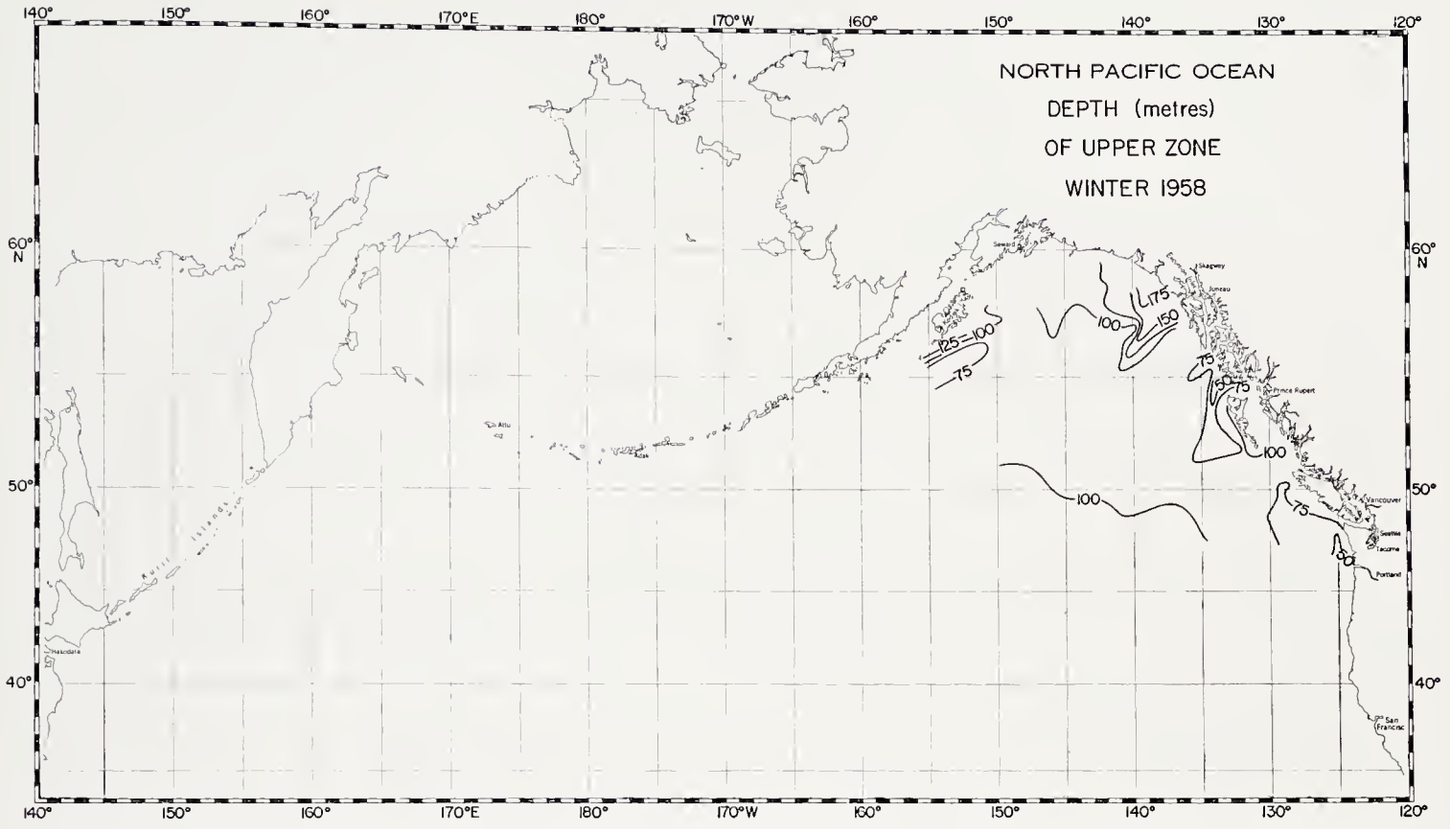


FIGURE 163. Depth (metres) of upper zone, winter 1958.

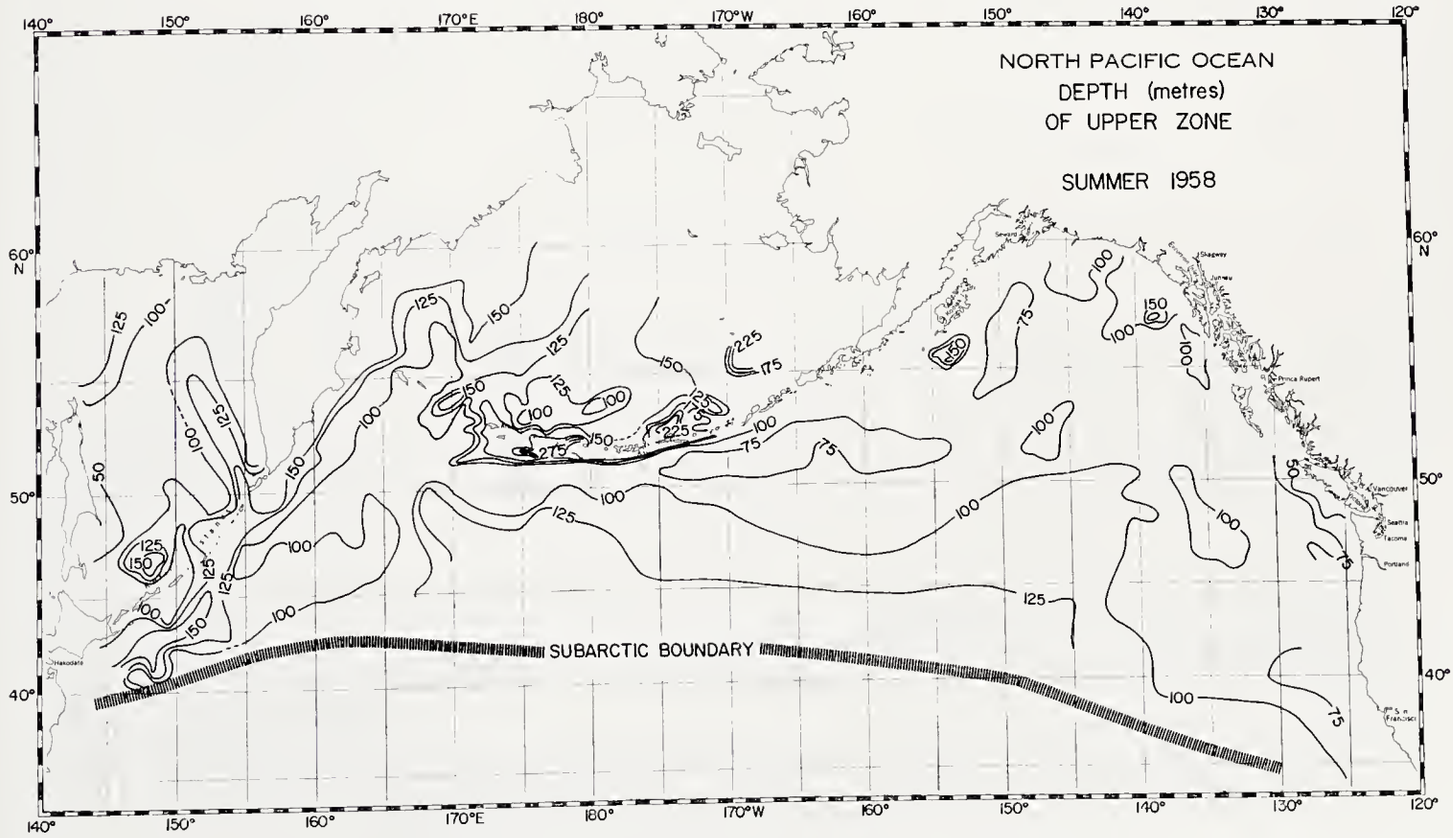


FIGURE 164. Depth (metres) of upper zone, summer 1958.

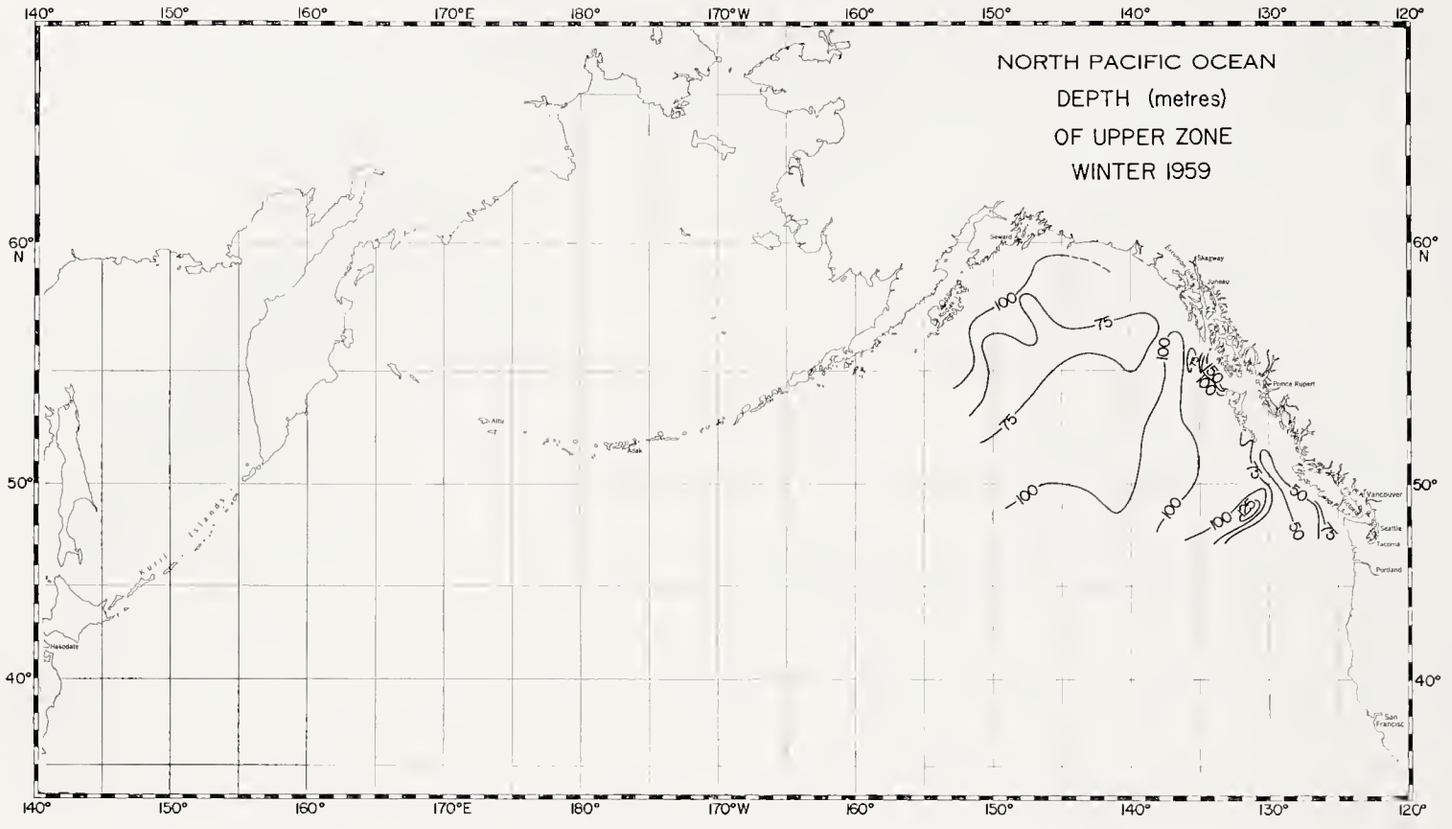


FIGURE 165. Depth (metres) of upper zone, winter 1959.

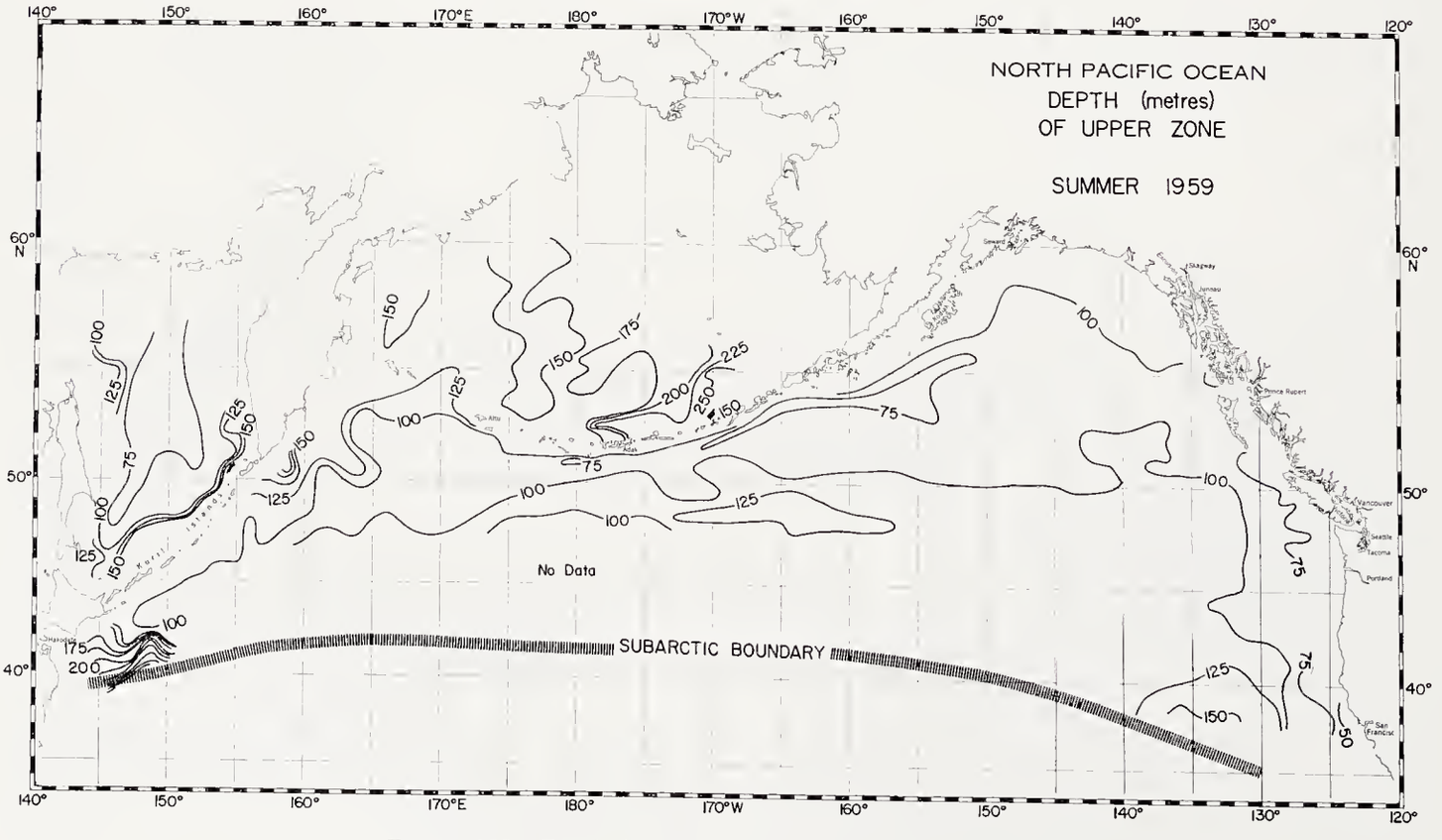


FIGURE 166. Depth (metres) of upper zone, summer 1959.

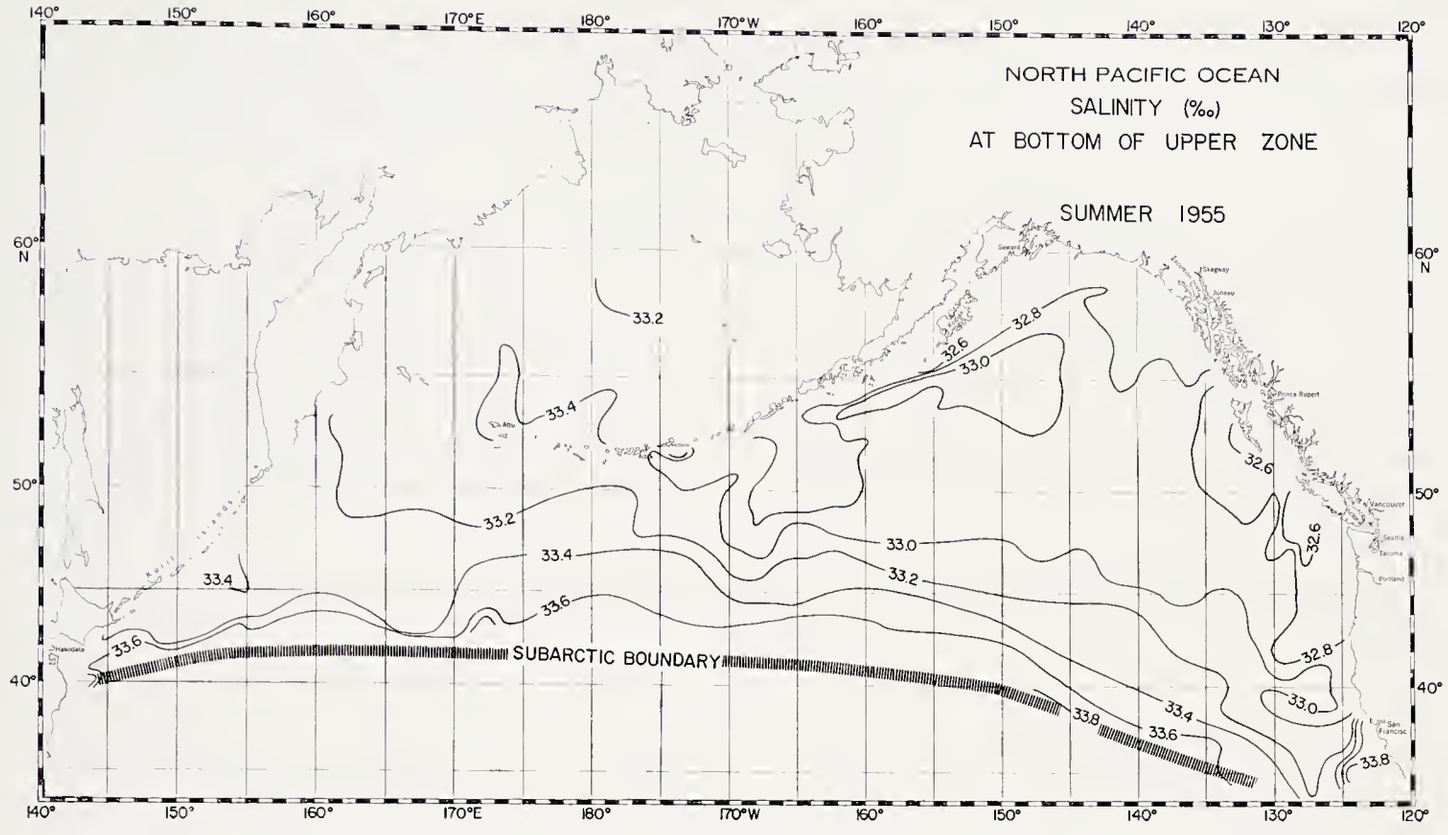


FIGURE 167. Salinity at bottom of upper zone, summer 1955.

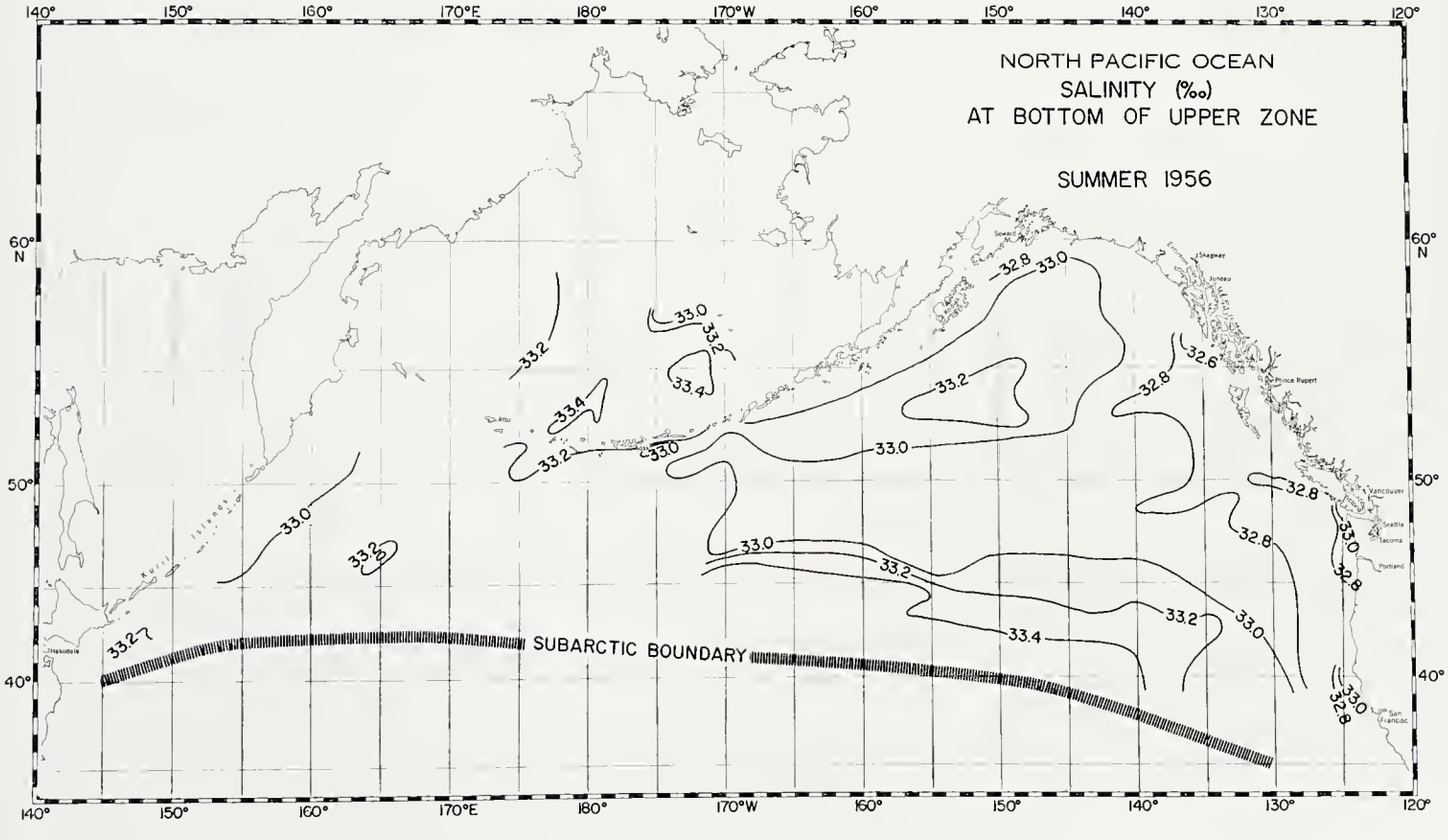


FIGURE 168. Salinity at bottom of upper zone, summer 1956.

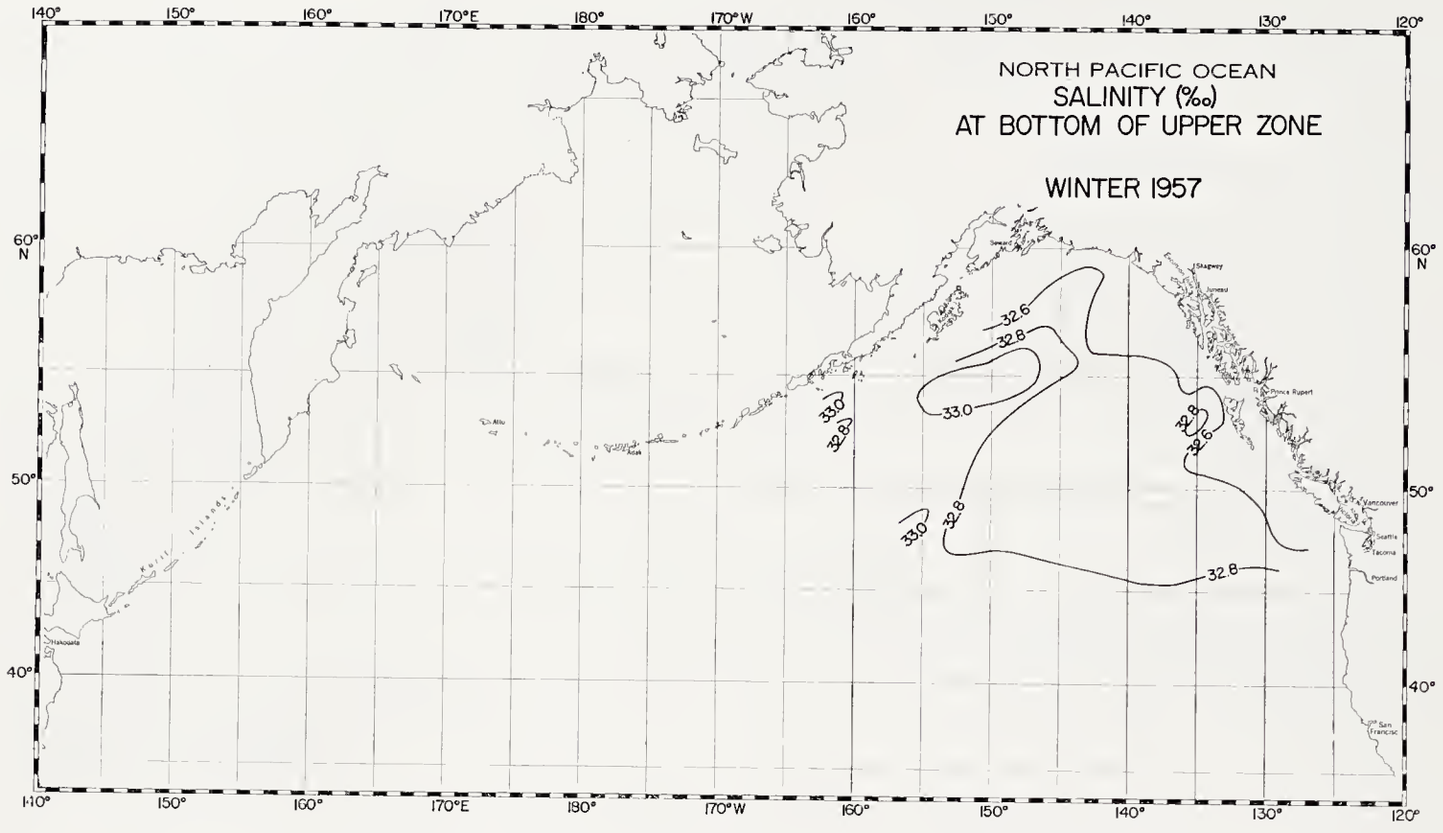


FIGURE 169. Salinity at bottom of upper zone, winter 1957.

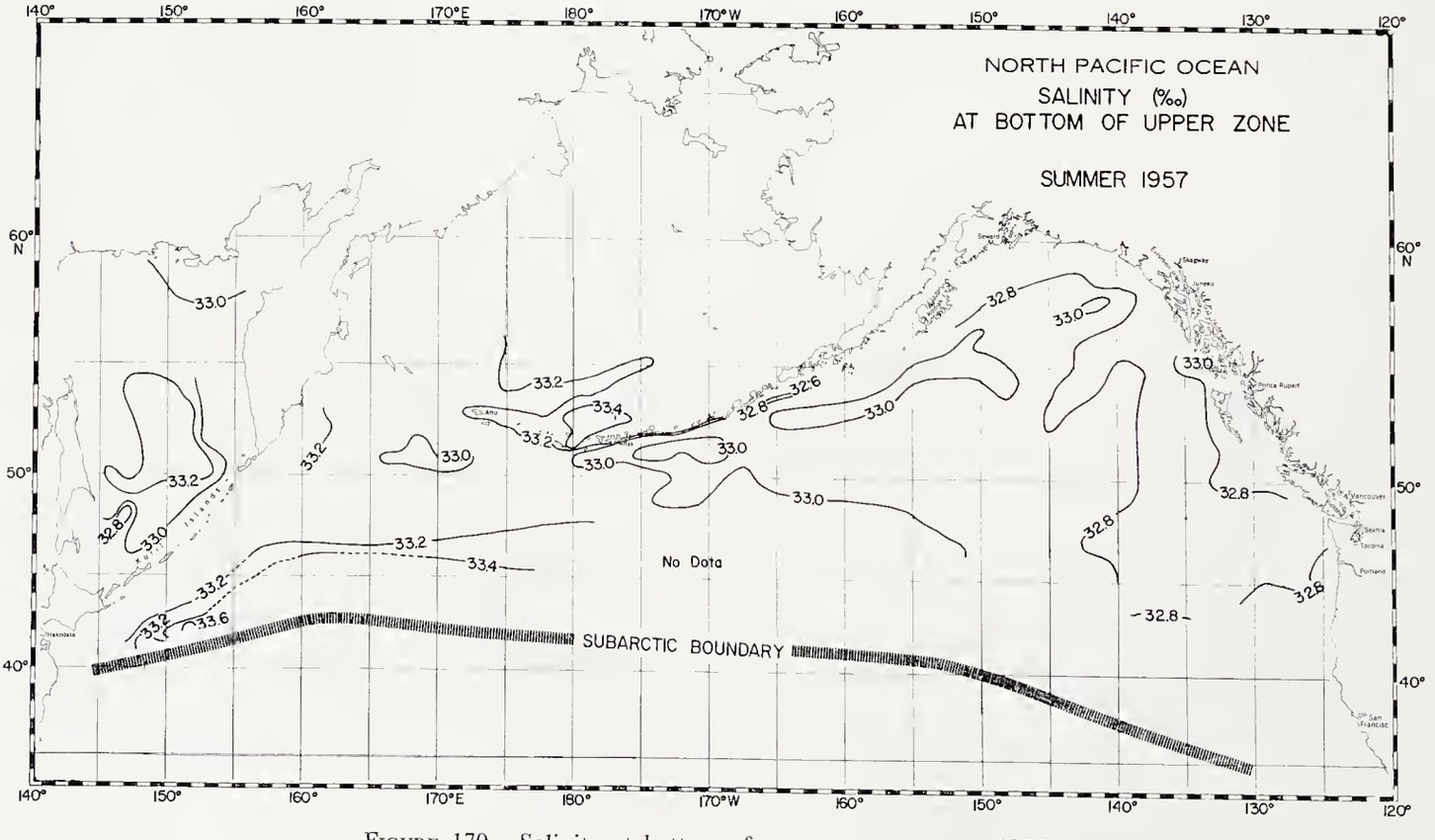


FIGURE 170. Salinity at bottom of upper zone, summer 1957.

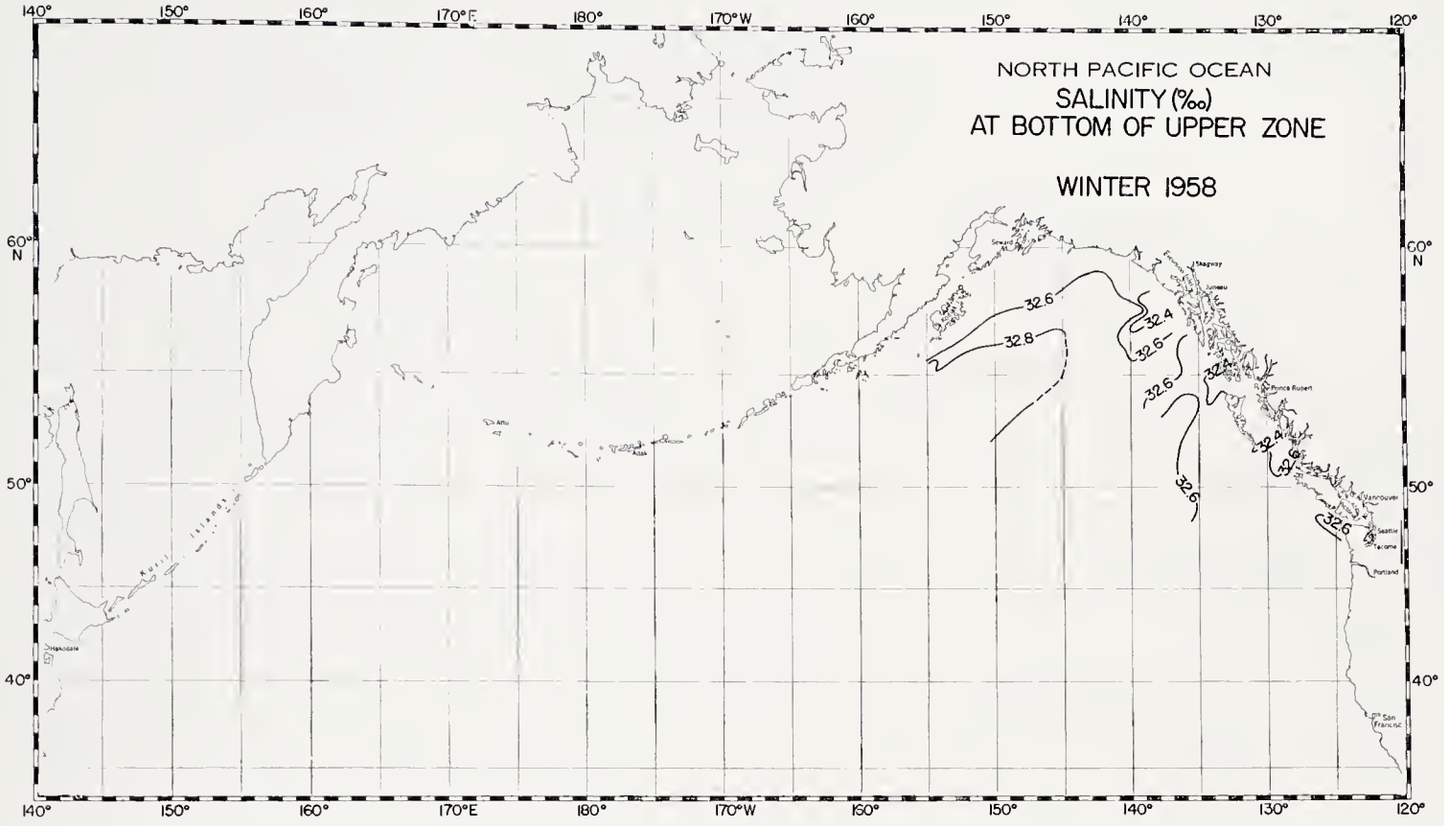


FIGURE 171. Salinity at bottom of upper zone, winter 1958.

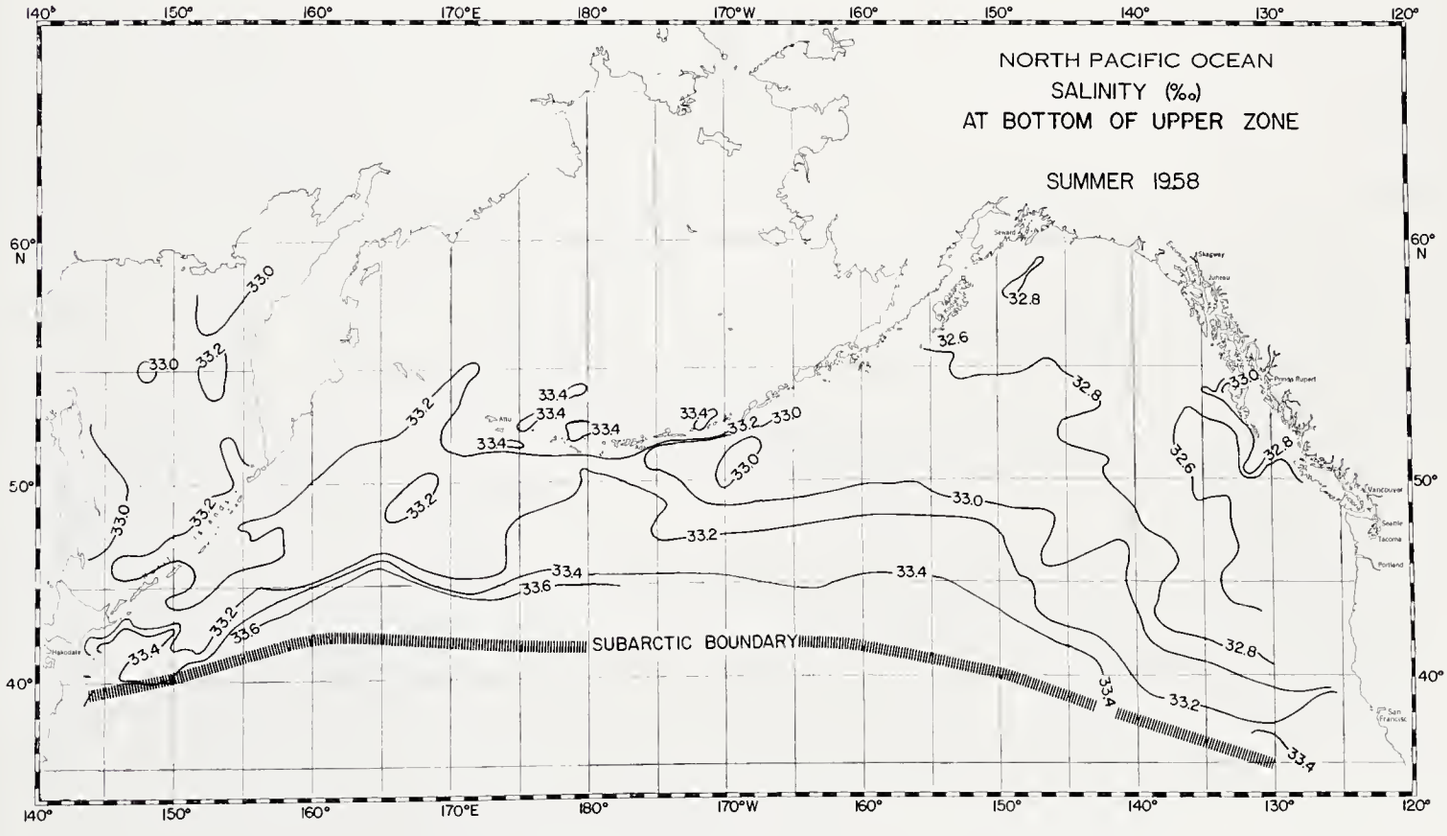


FIGURE 172. Salinity at bottom of upper zone, summer 1958.

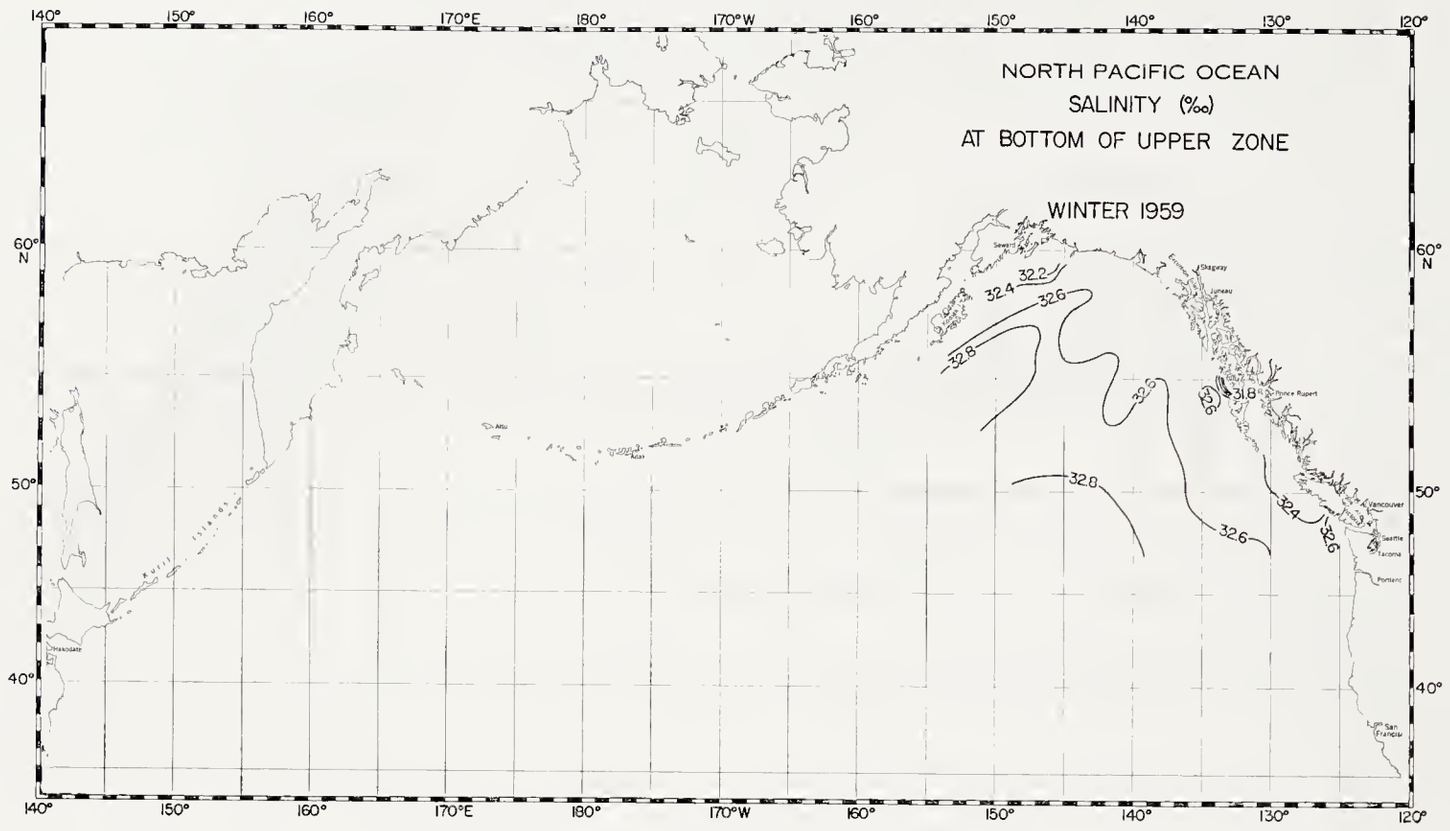


FIGURE 173. Salinity at bottom of upper zone, winter 1959.

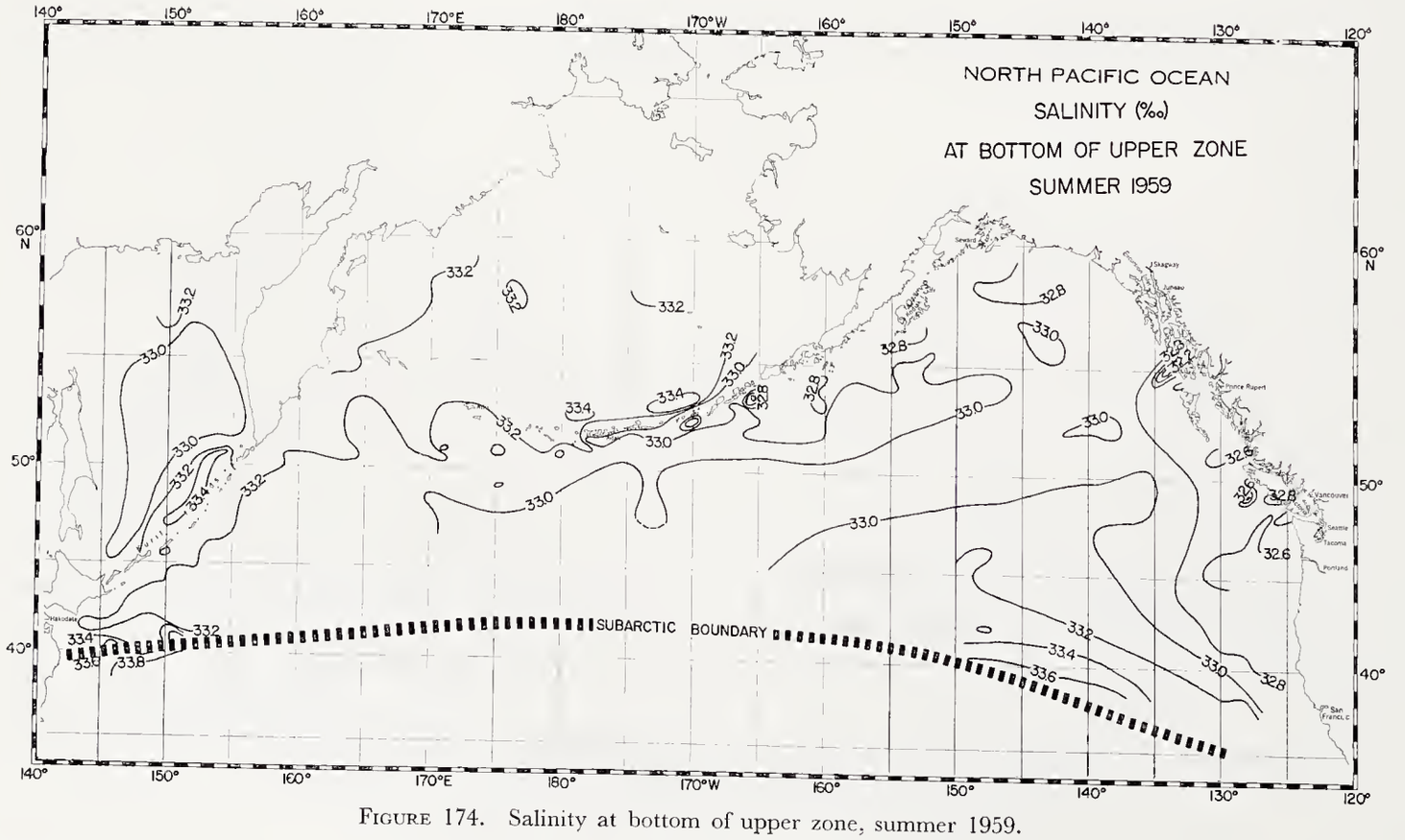


FIGURE 174. Salinity at bottom of upper zone, summer 1959.

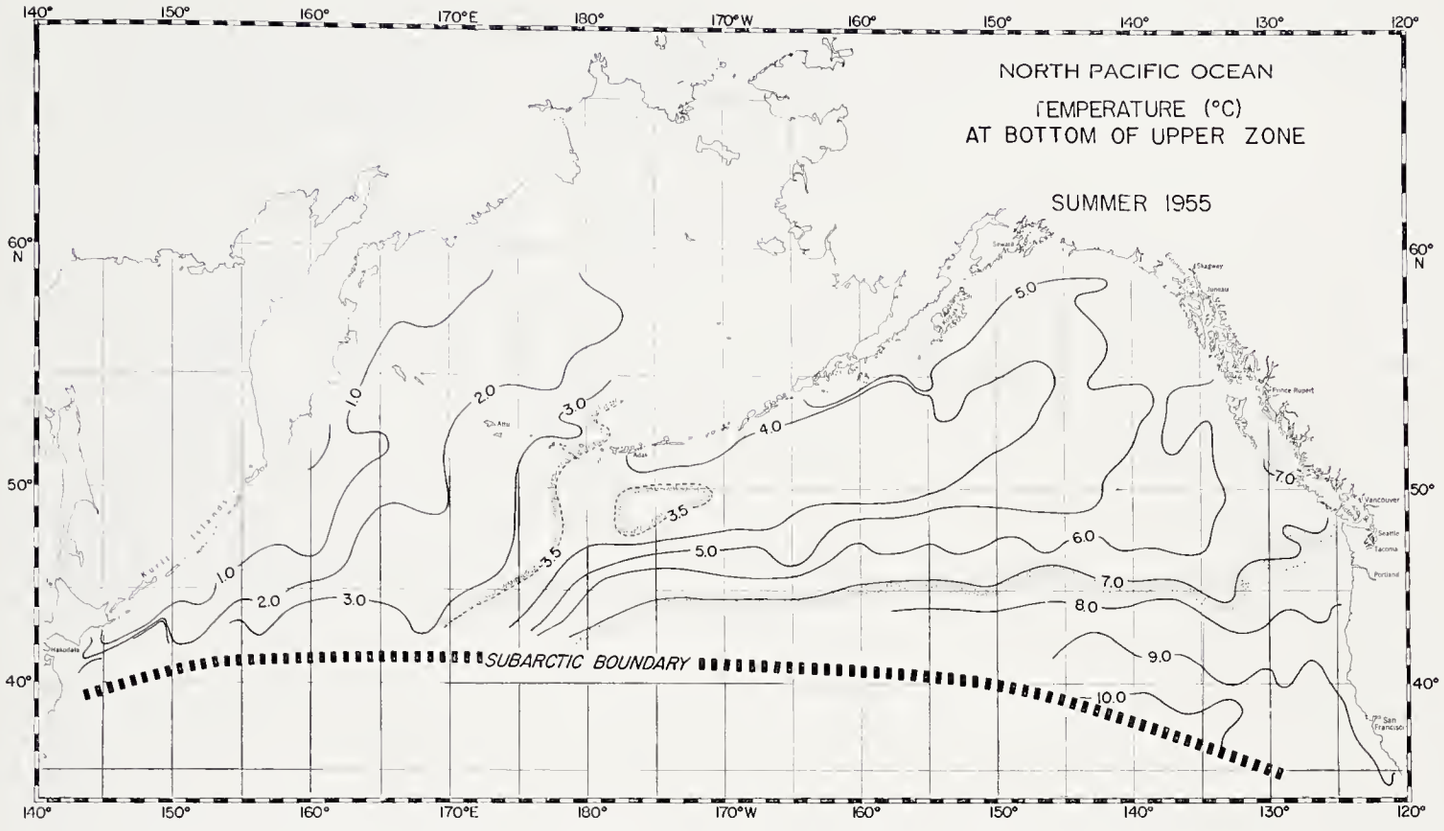


FIGURE 175. Temperature at bottom of upper zone, summer 1955.

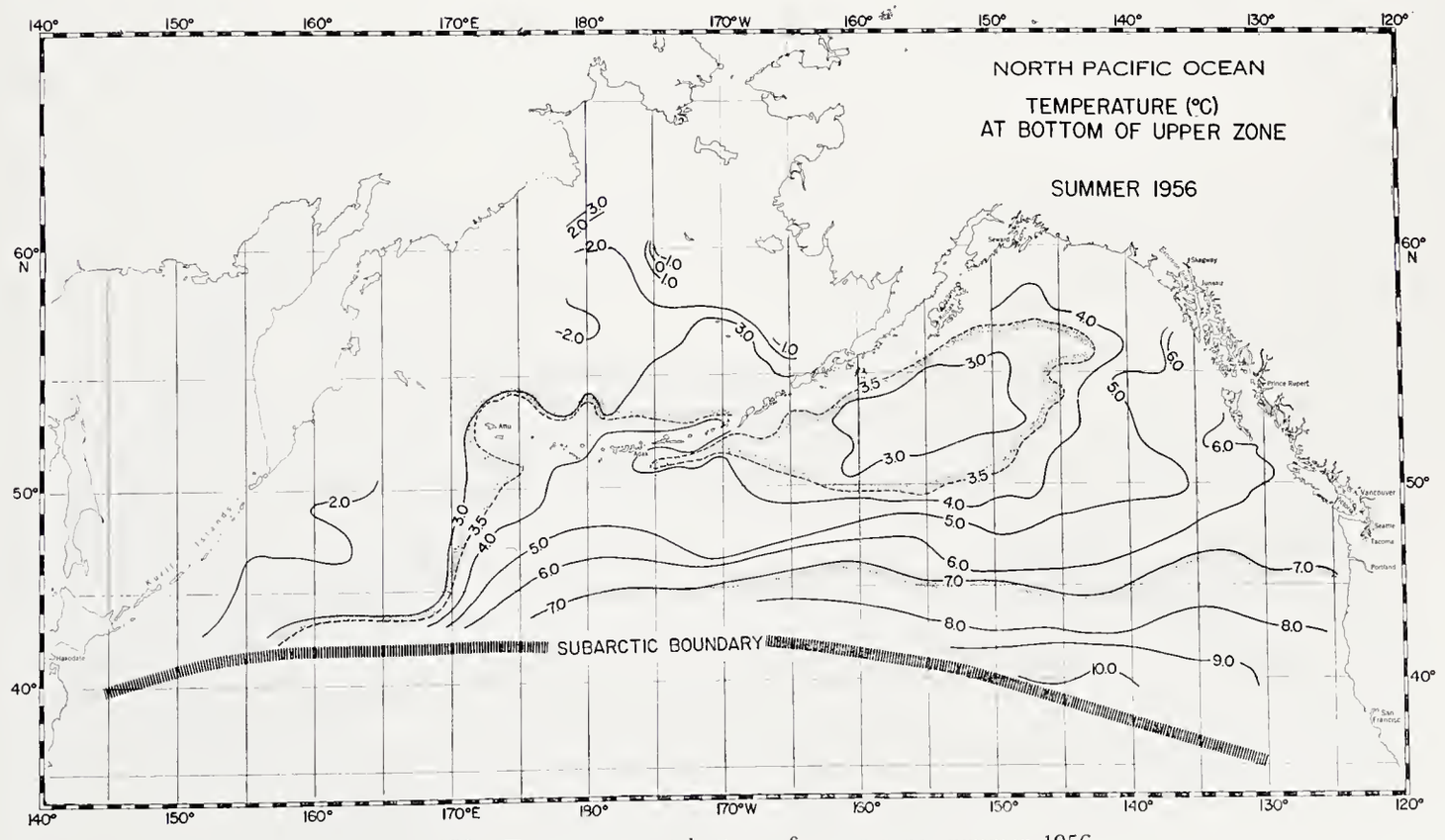


FIGURE 176. Temperature at bottom of upper zone, summer 1956.

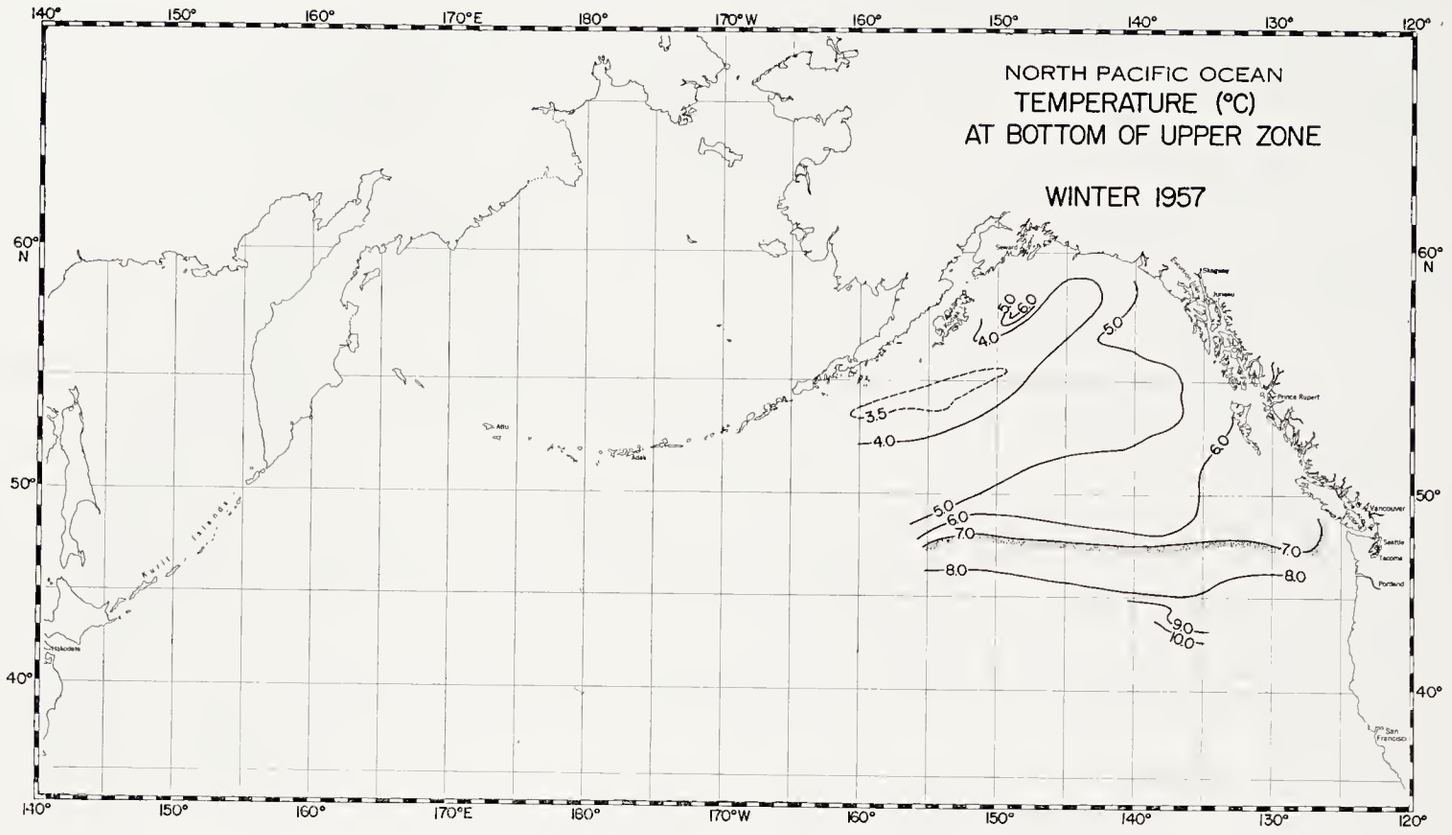


FIGURE 177. Temperature at bottom of upper zone, winter 1957.

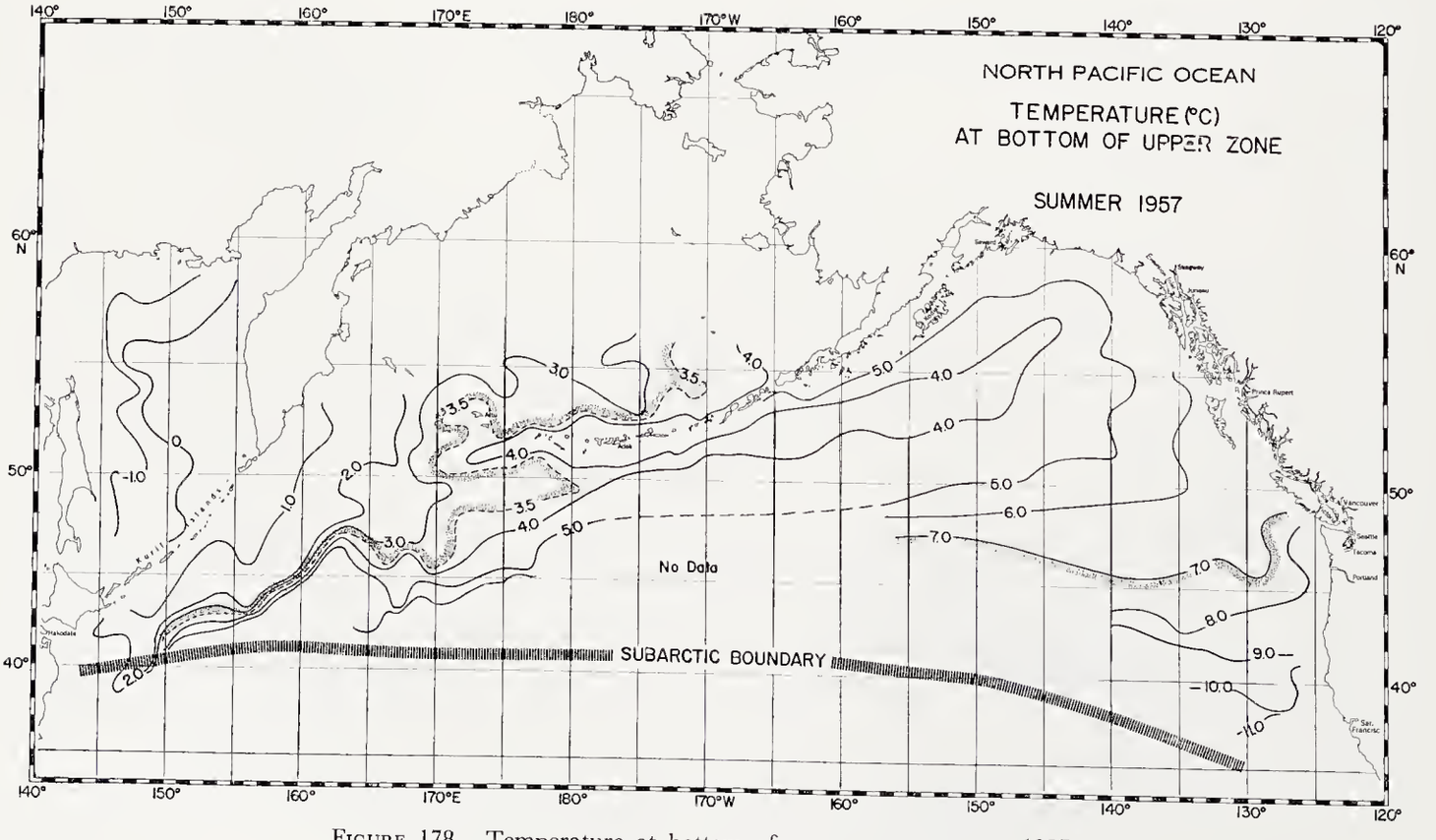


FIGURE 178. Temperature at bottom of upper zone, summer 1957.

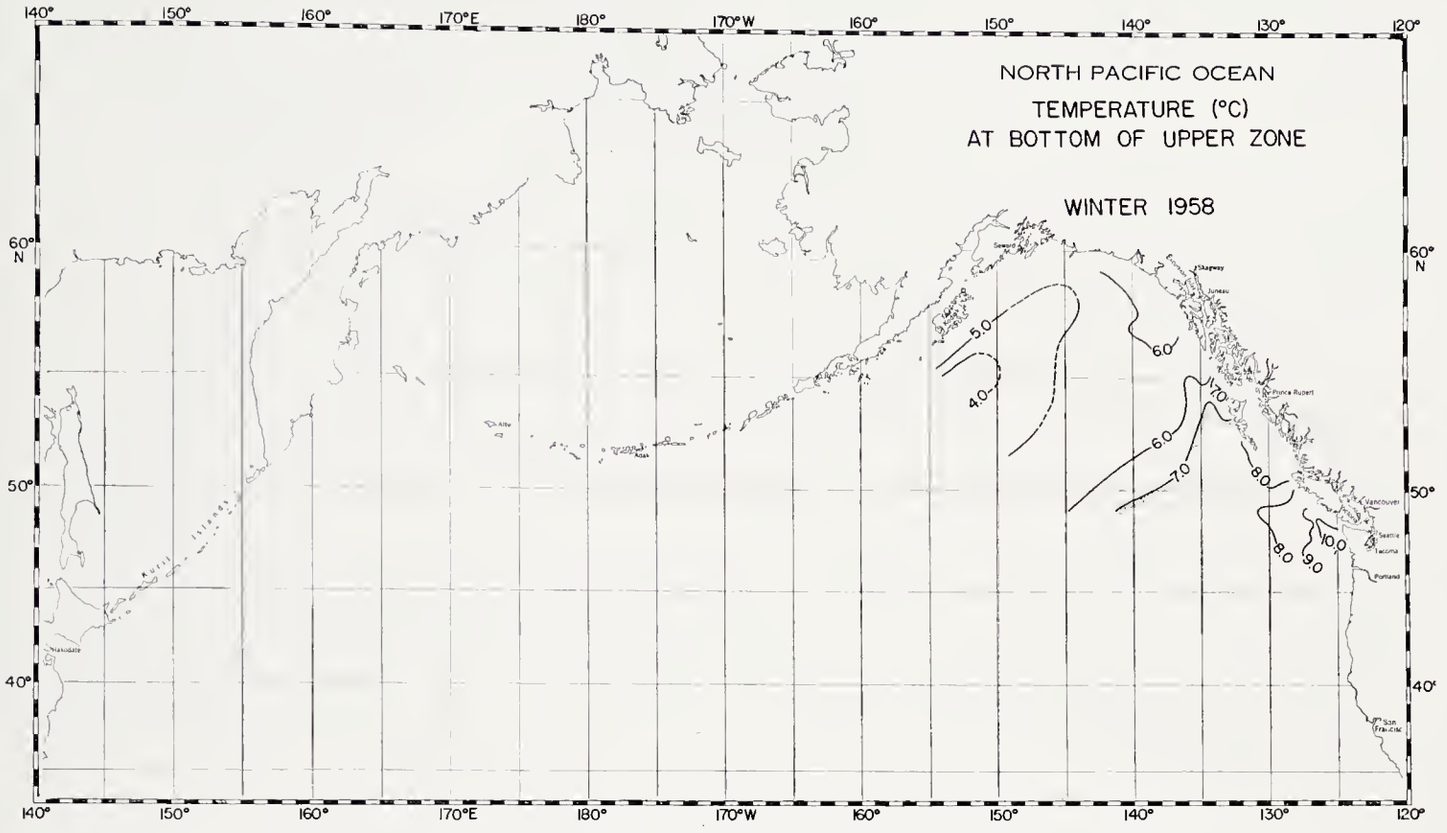


FIGURE 179. Temperature at bottom of upper zone, winter 1958.

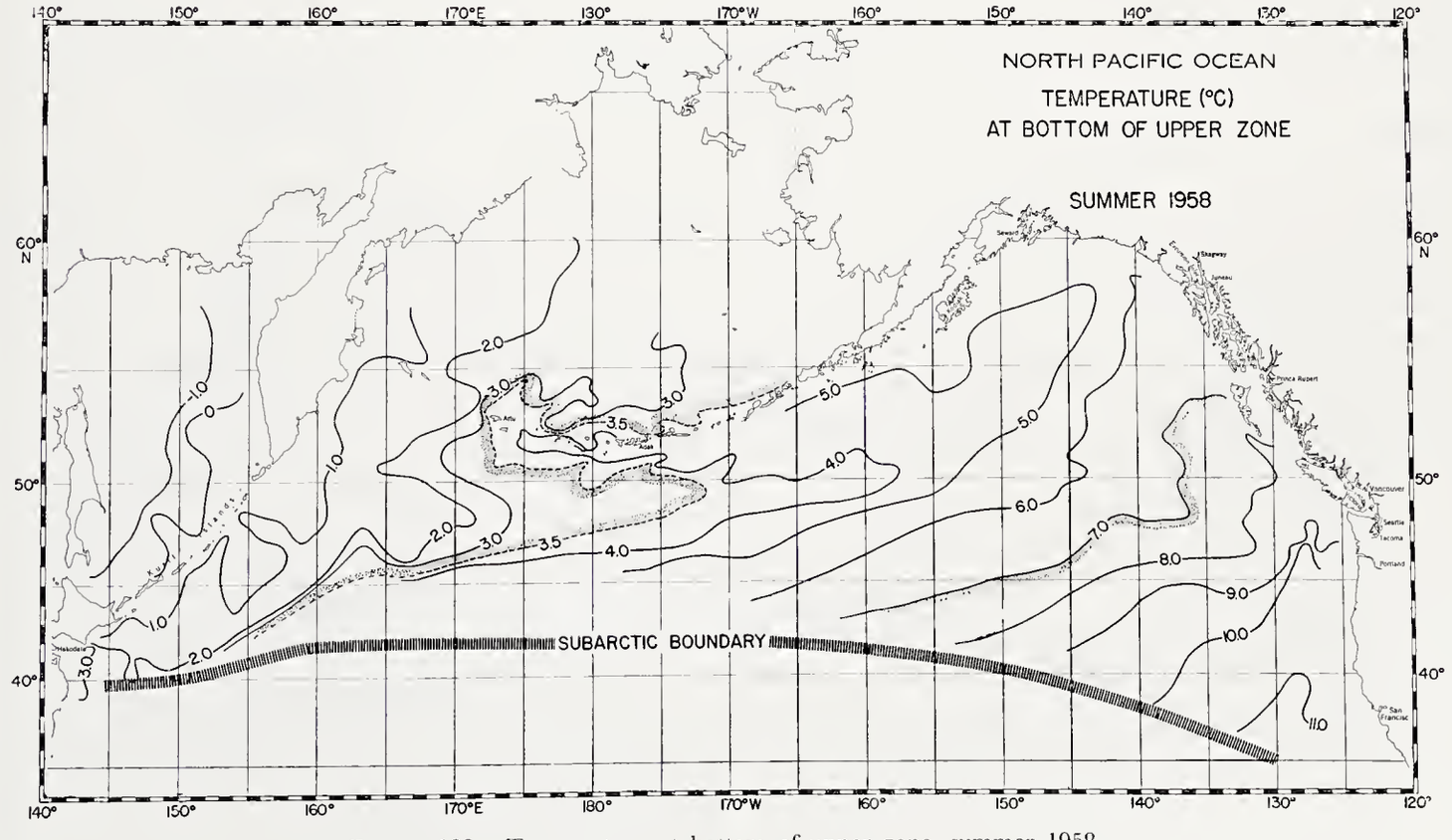


FIGURE 180. Temperature at bottom of upper zone, summer 1958.

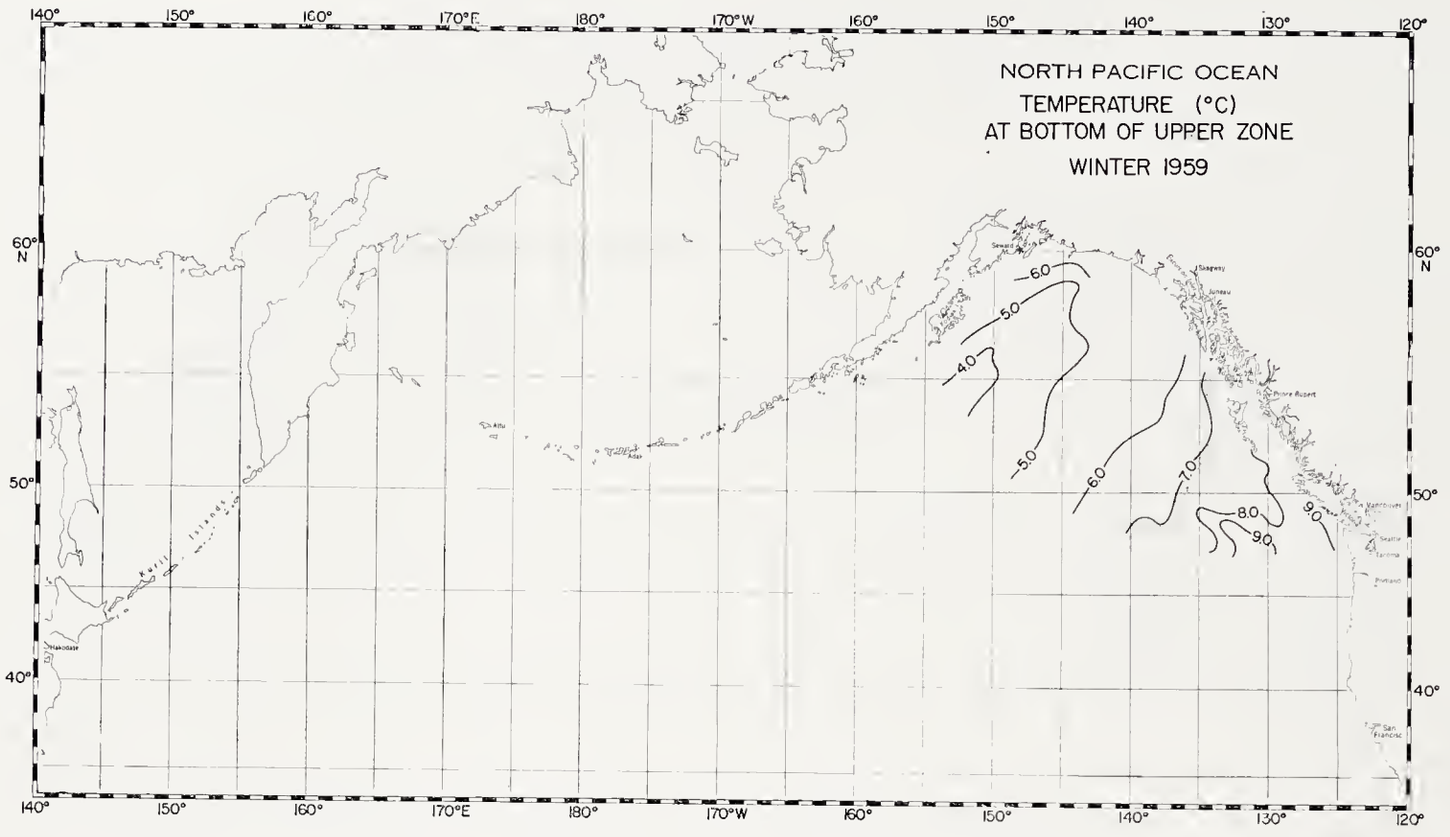


FIGURE 181. Temperature at bottom of upper zone, winter 1959.

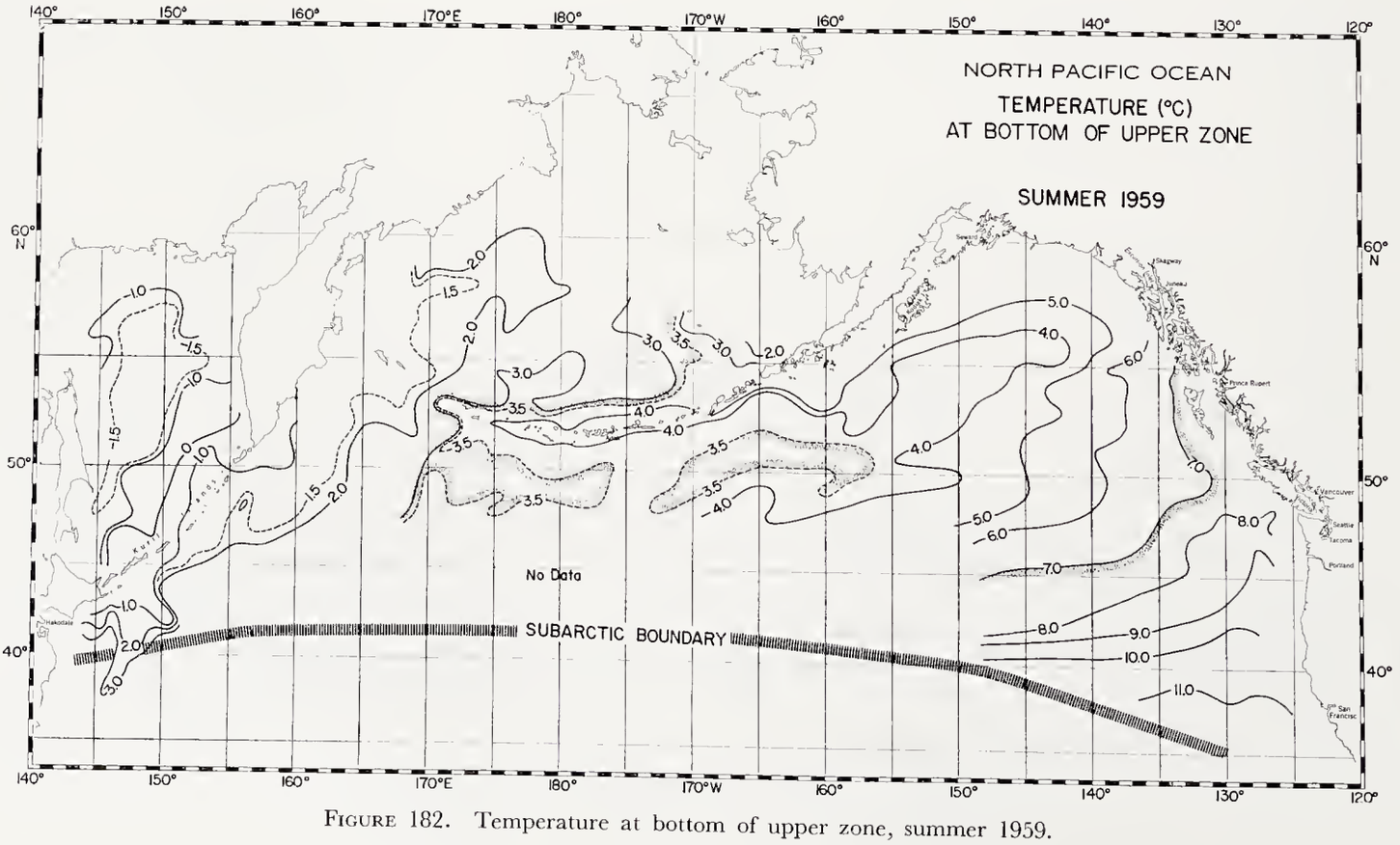


FIGURE 182. Temperature at bottom of upper zone, summer 1959.

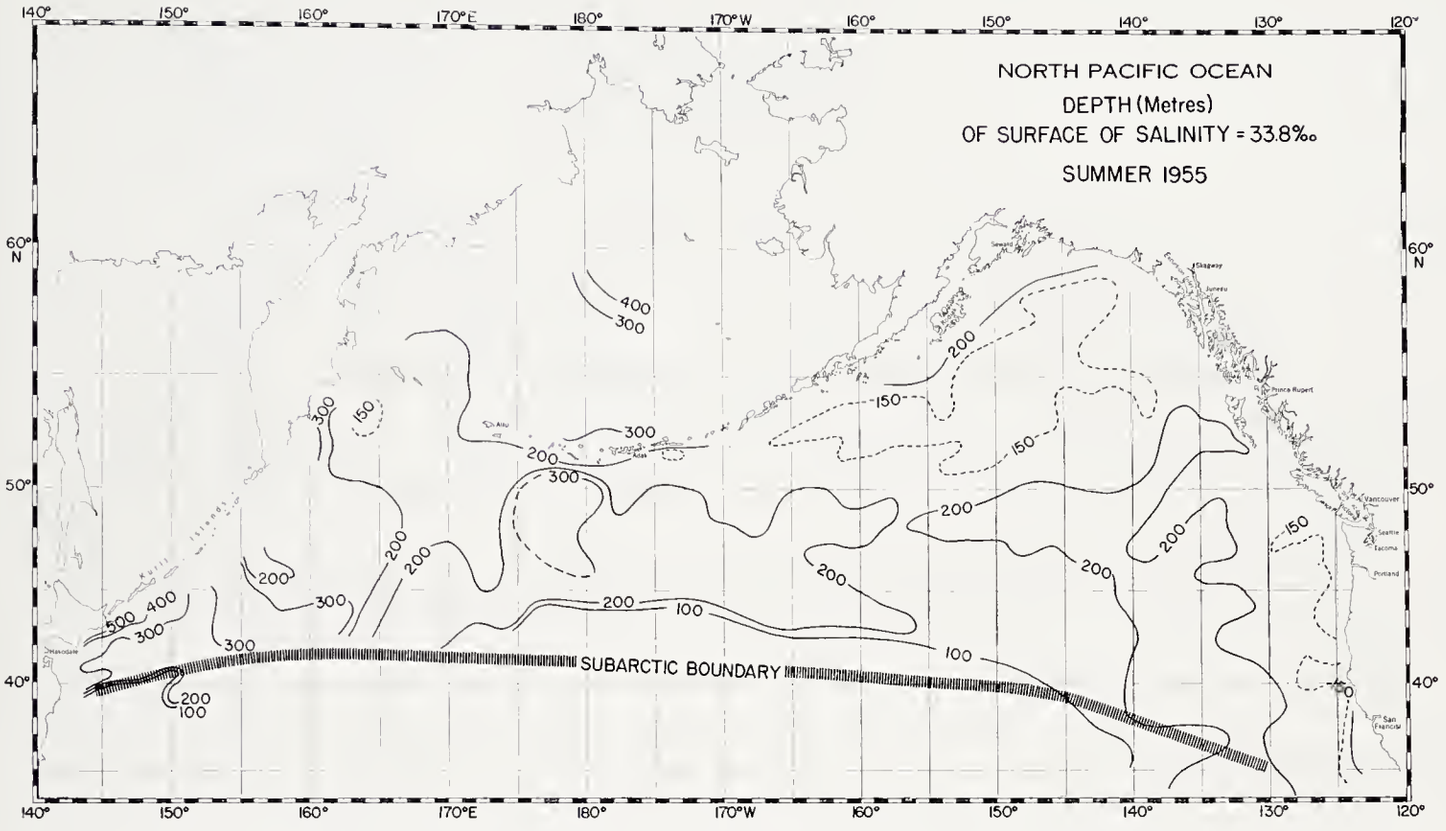


FIGURE 183. Depth (metres) of surface of salinity=33.8‰, summer 1955.

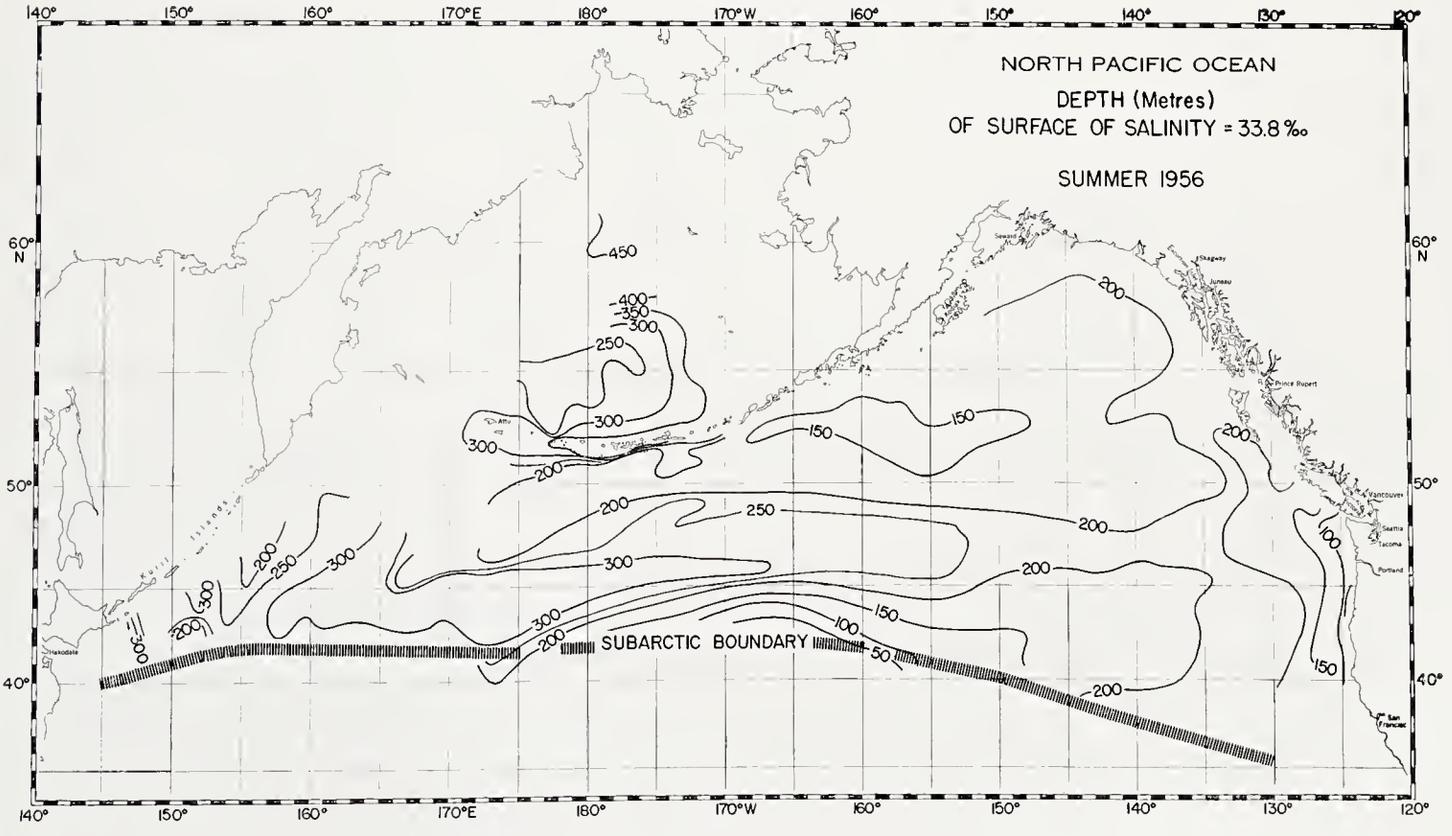


FIGURE 184. Depth (metres) of surface of salinity=33.8‰, summer 1956.

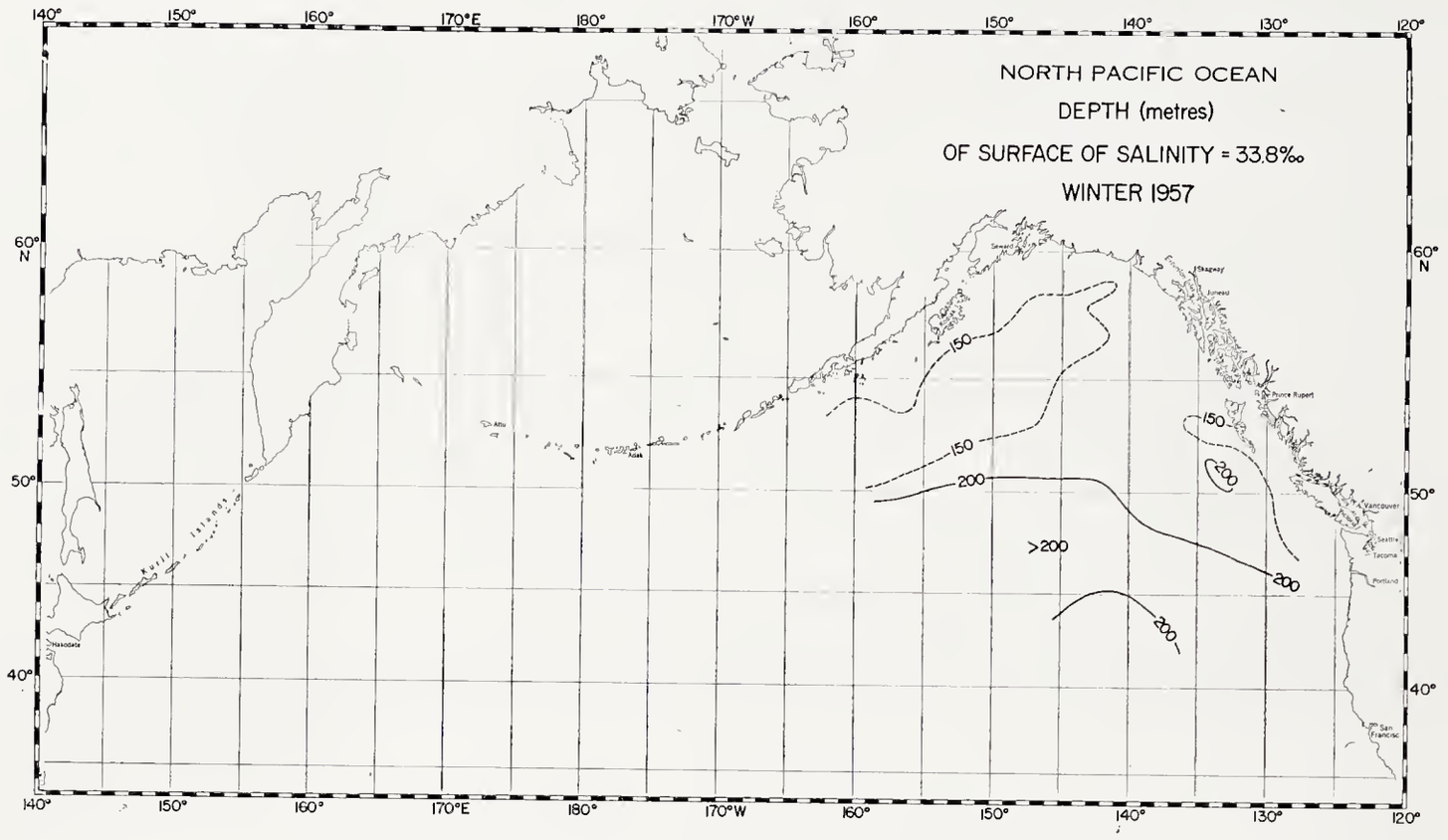


FIGURE 185. Depth (metres) of surface of salinity=33.8‰, winter 1957.

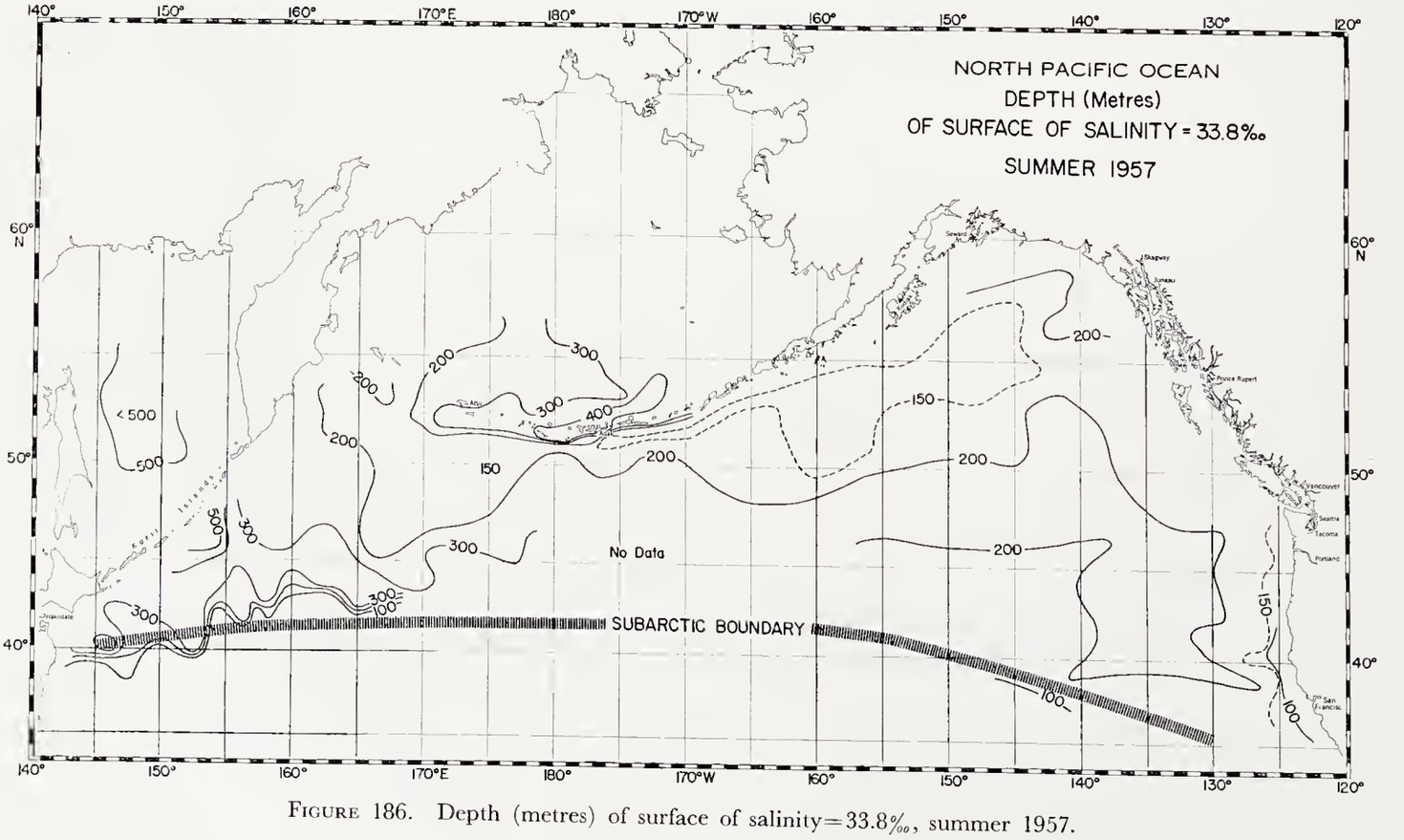


FIGURE 186. Depth (metres) of surface of salinity=33.8‰, summer 1957.

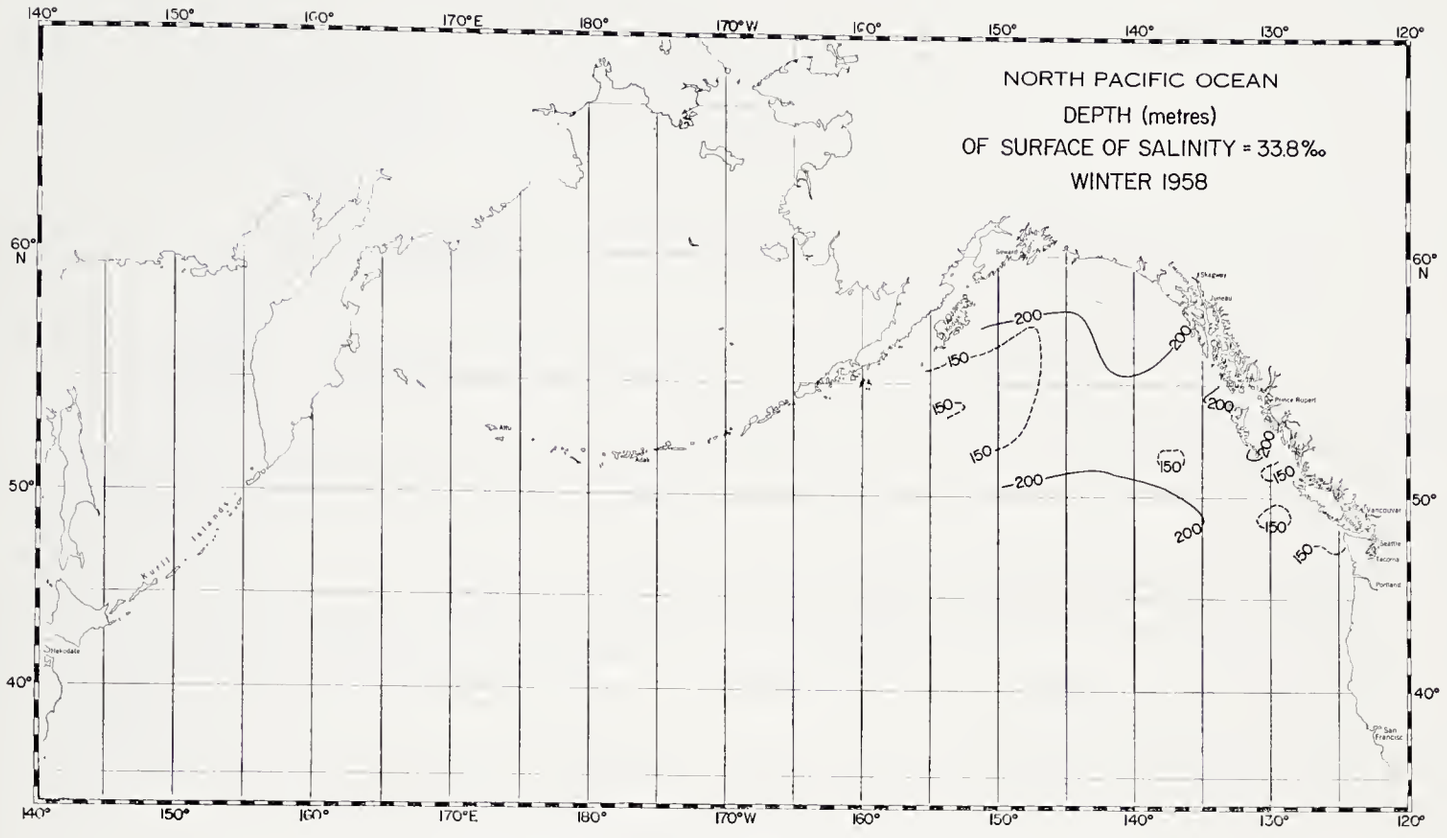


FIGURE 187. Depth (metres) of surface of salinity=33.8‰, winter 1958.

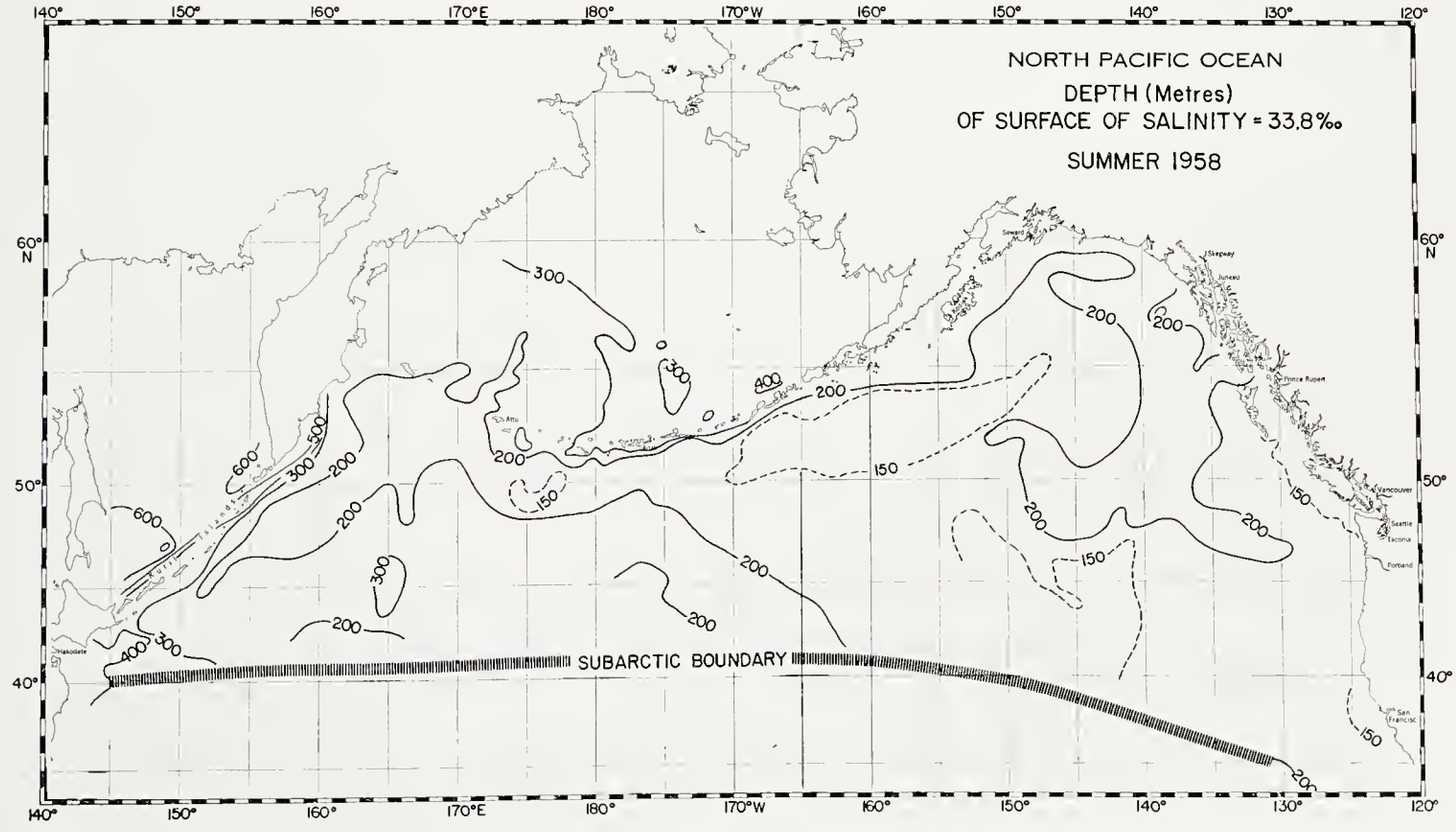


FIGURE 188. Depth (metres) of surface of salinity=33.8‰, summer 1958.

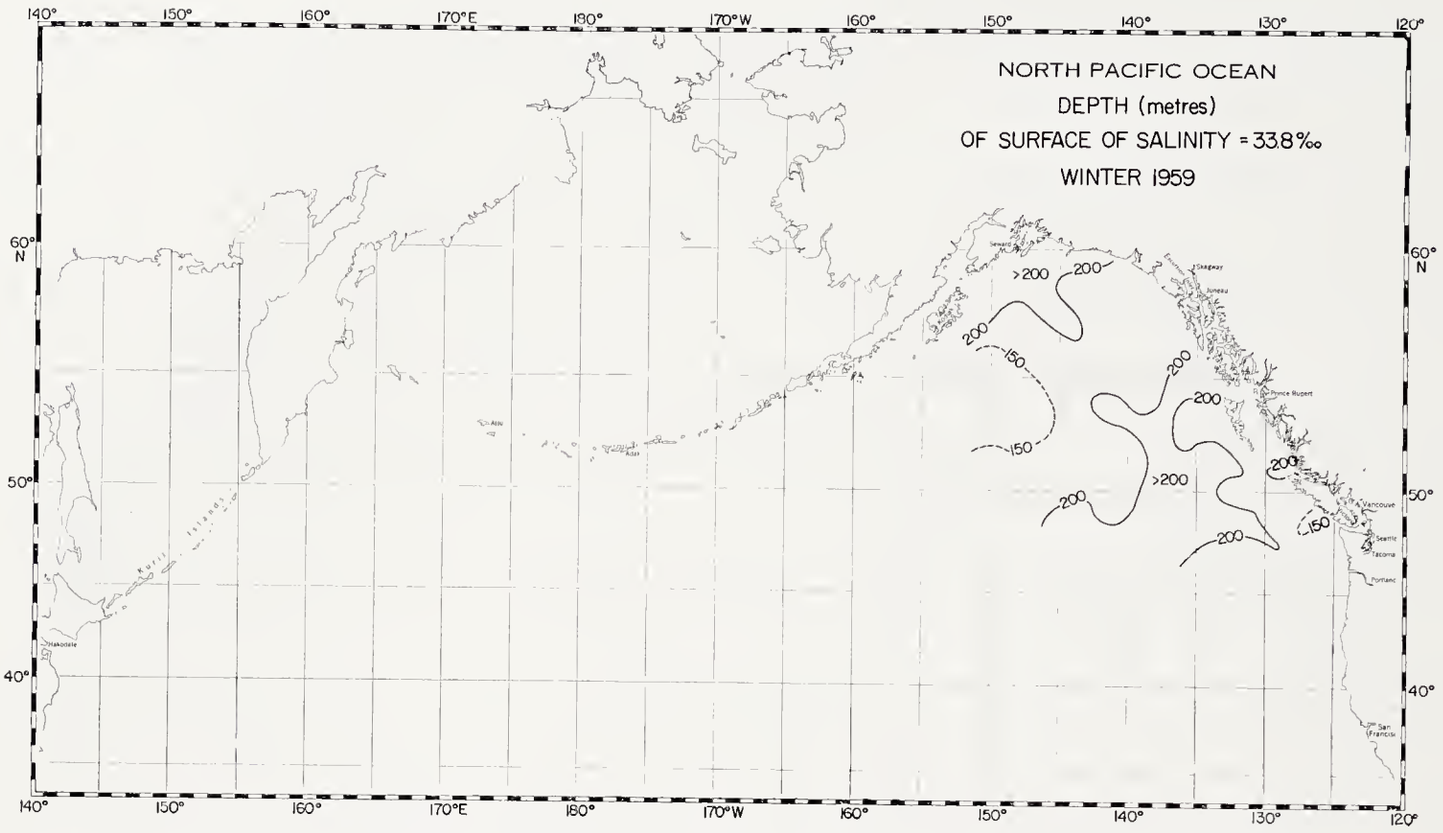


FIGURE 189. Depth (metres) of surface of salinity=33.8‰, winter 1959.

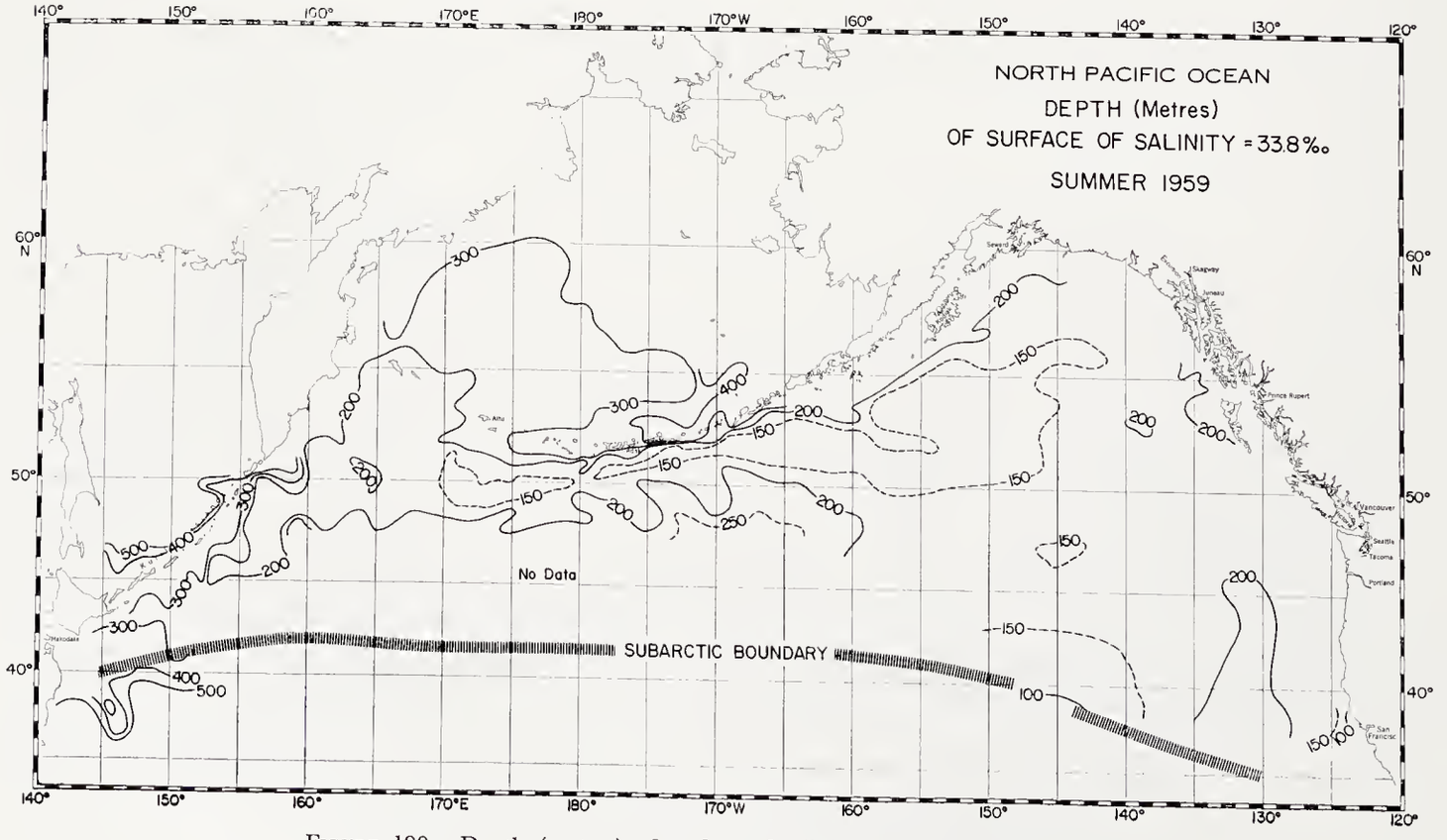


FIGURE 190. Depth (metres) of surface of salinity=33.8‰, summer 1959.

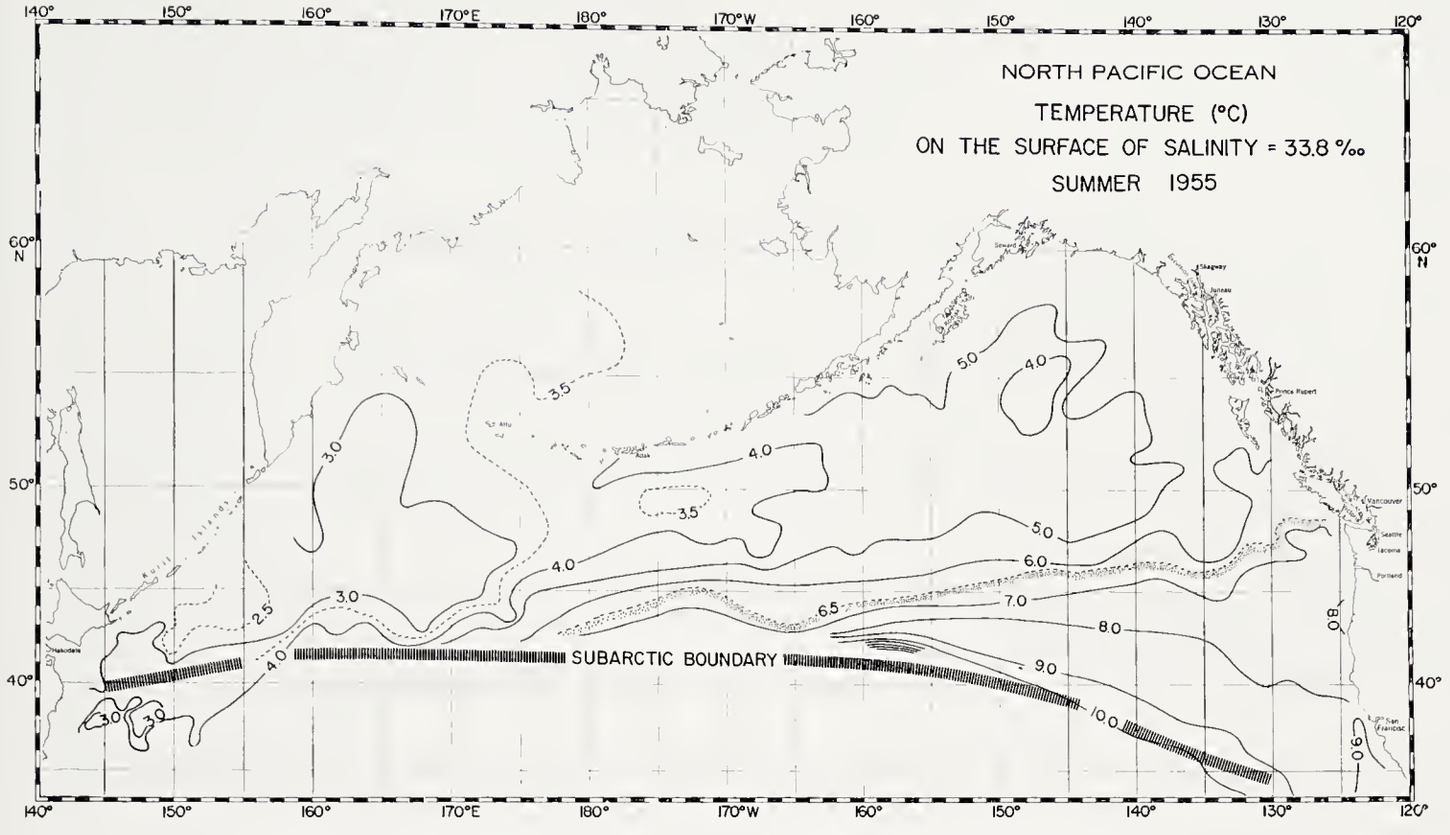


FIGURE 191. Temperature on the surface of salinity=33.8‰, summer 1955.

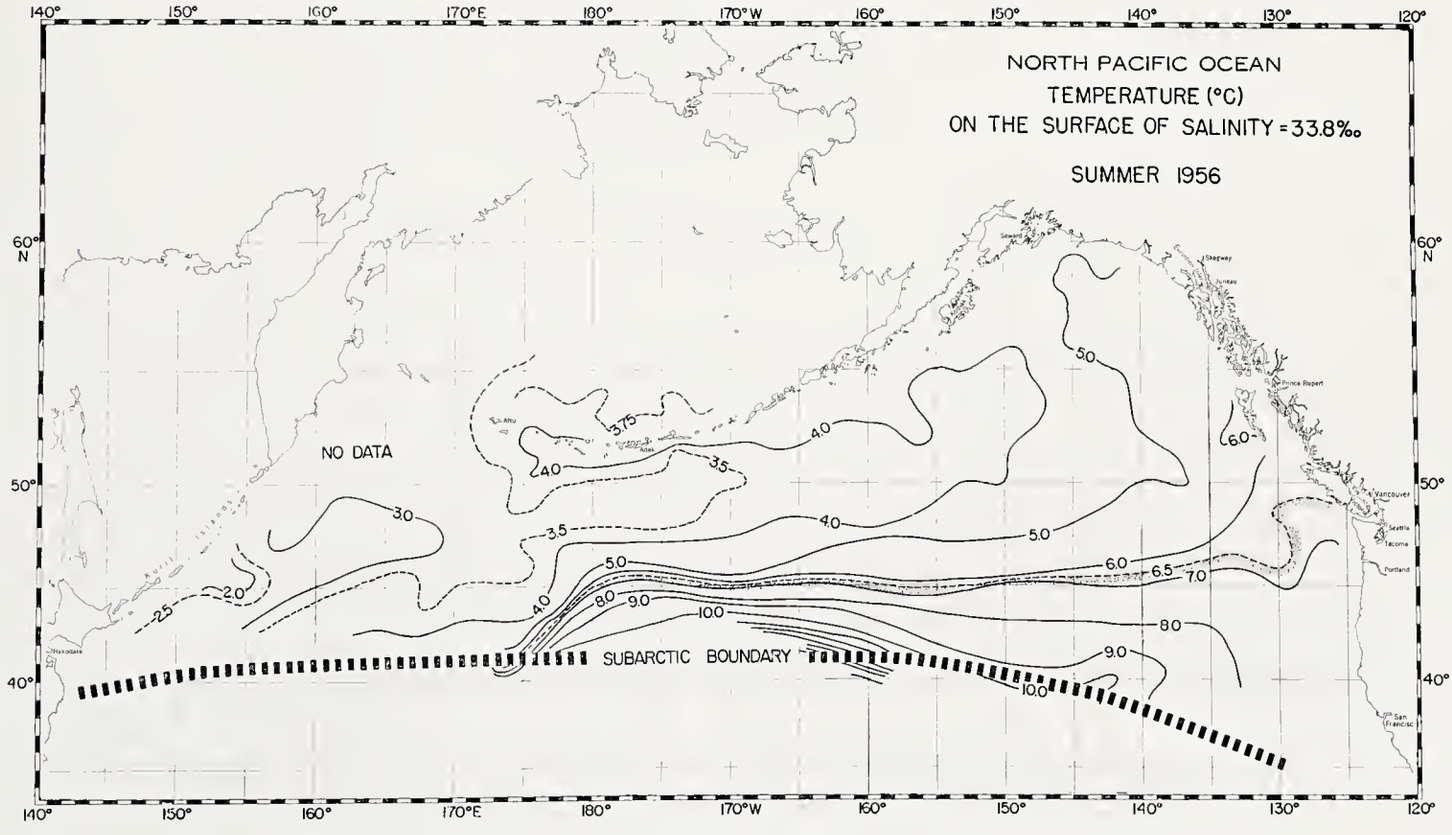


FIGURE 192. Temperature on the surface of salinity=33.8‰, summer 1956.

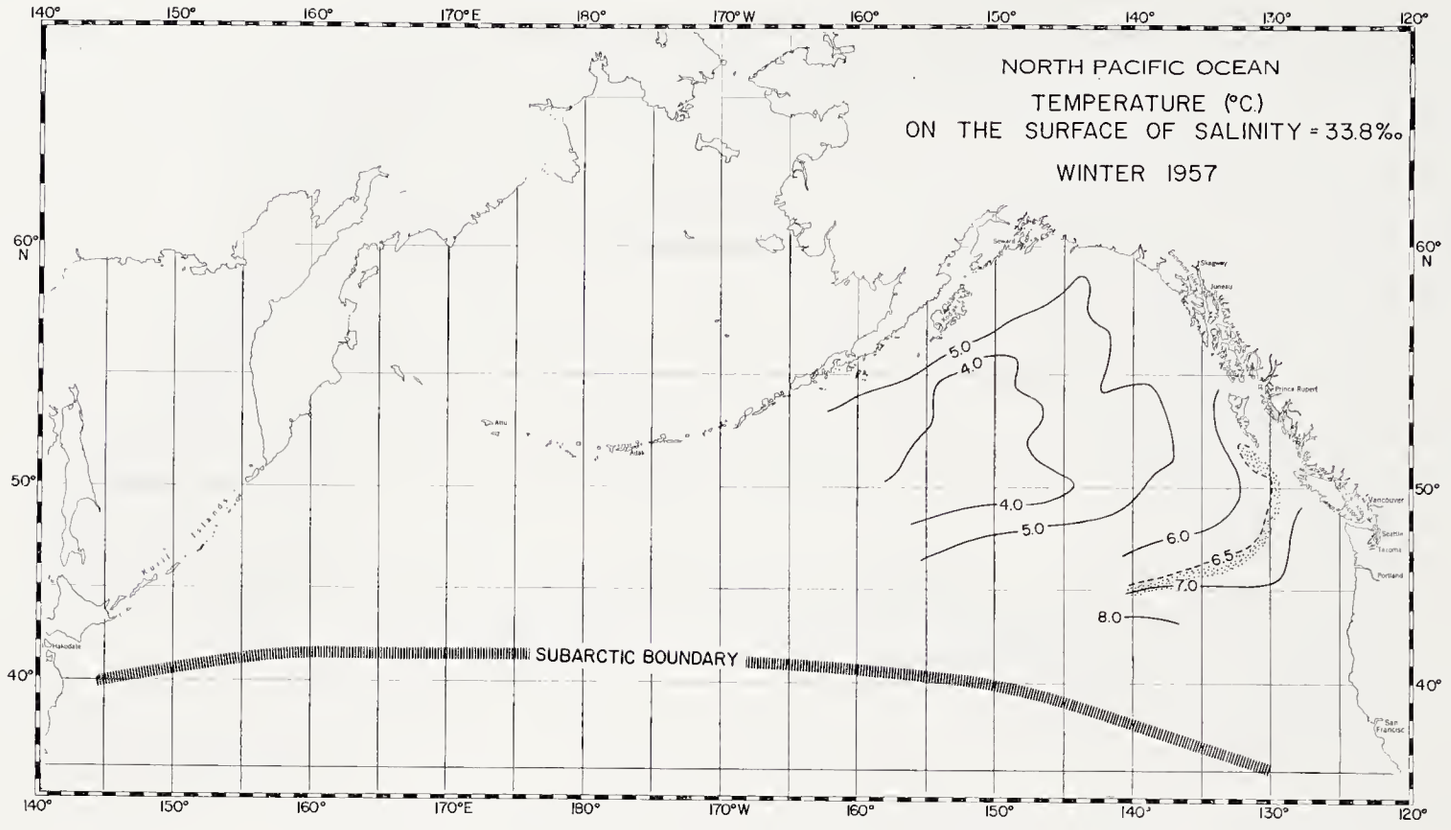


FIGURE 193. Temperature on the surface of salinity=33.8‰, winter 1957.

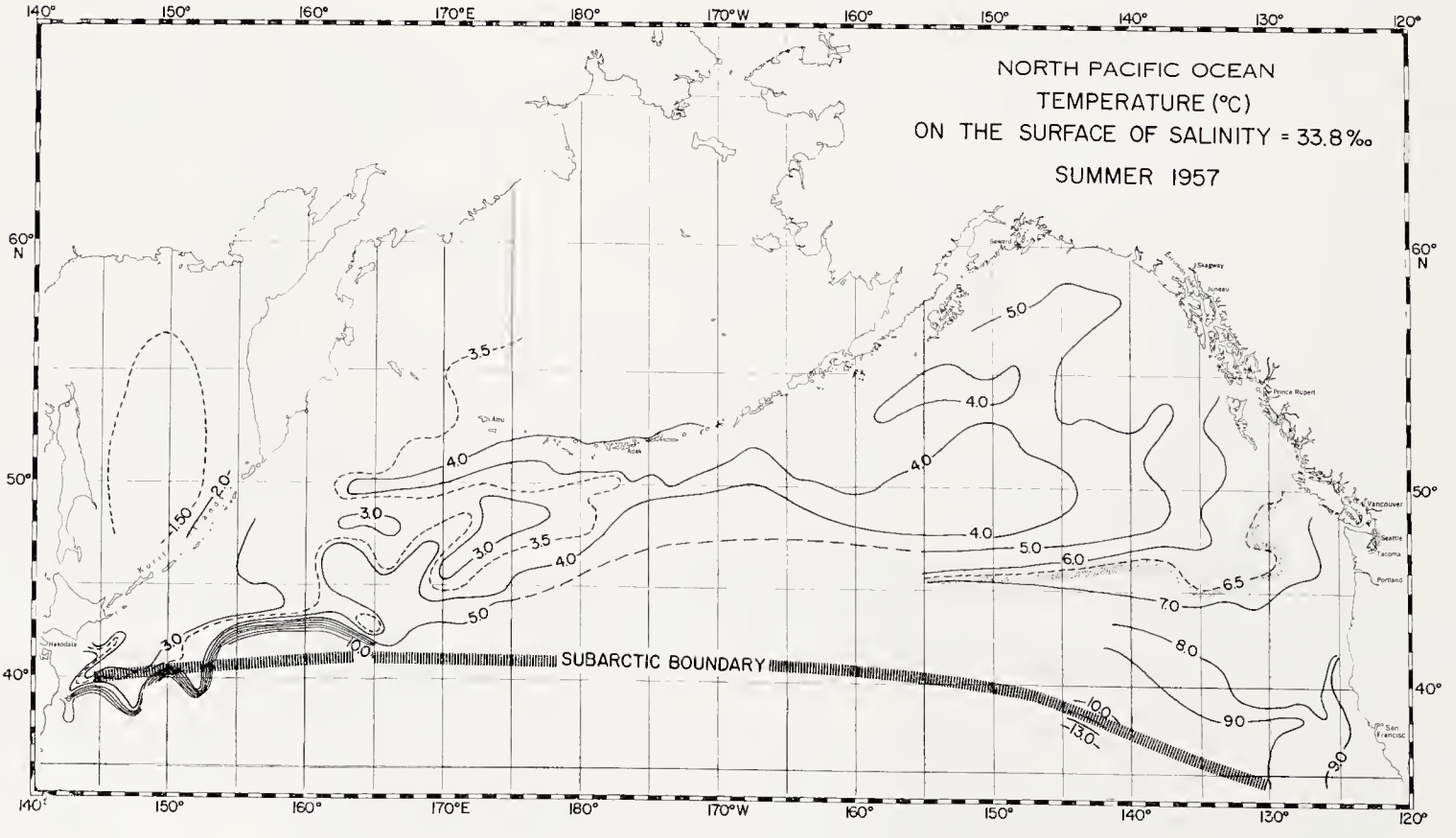


FIGURE 194. Temperature on the surface of salinity=33.8‰, summer 1957.

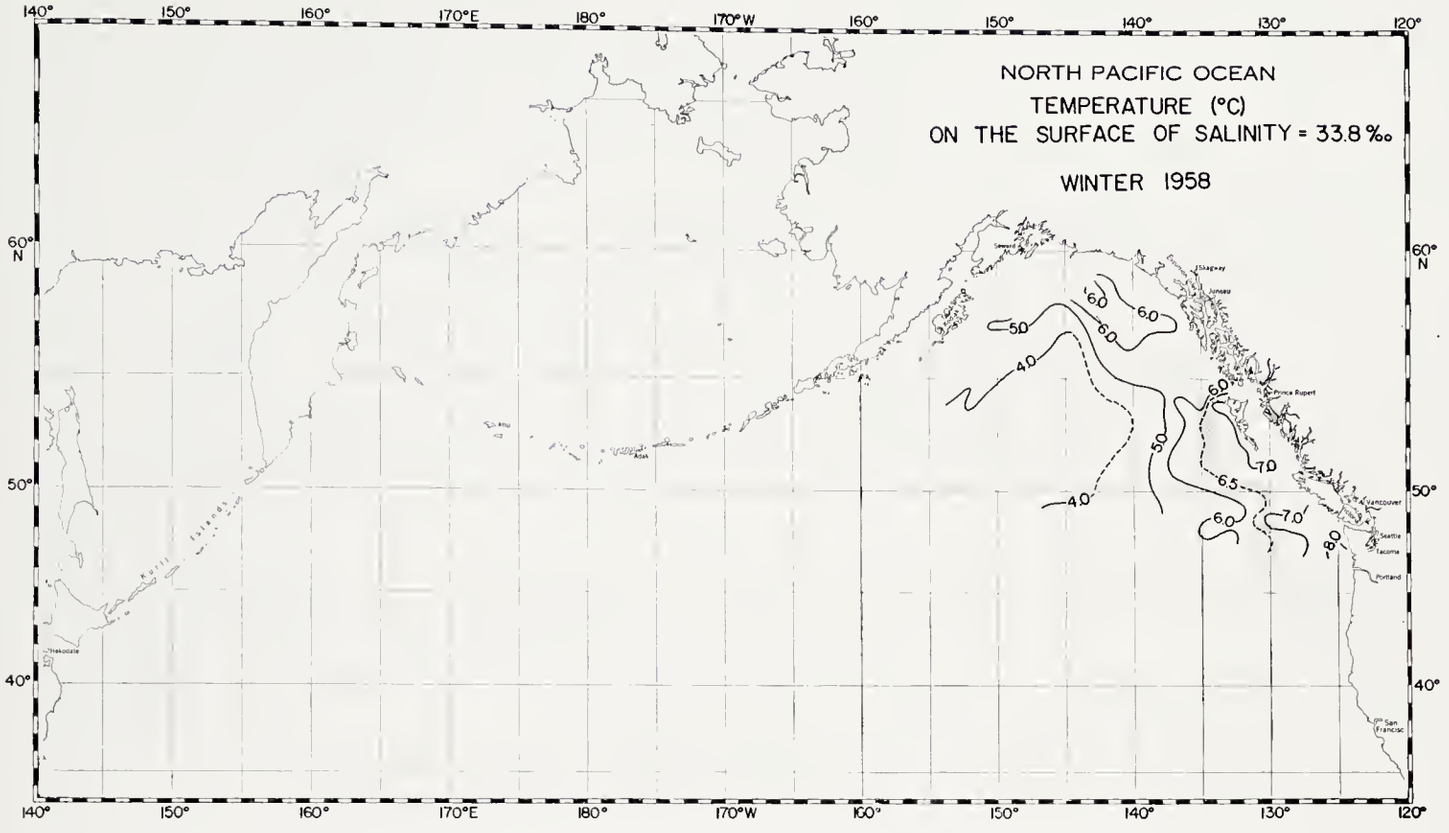


FIGURE 195. Temperature on the surface of salinity=33.8‰, winter 1958.

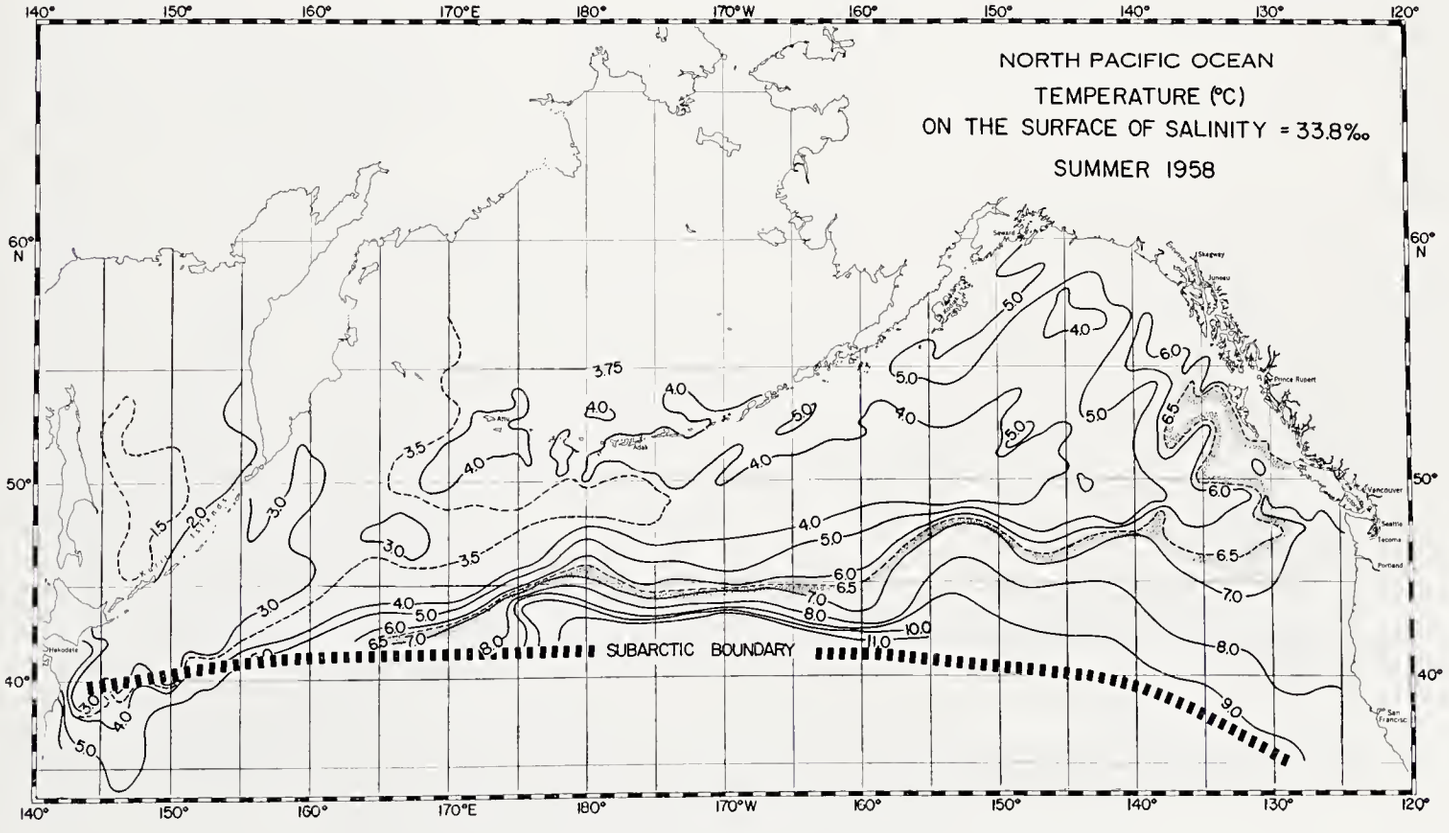


FIGURE 196. Temperature on the surface of salinity=33.8‰, summer 1958.

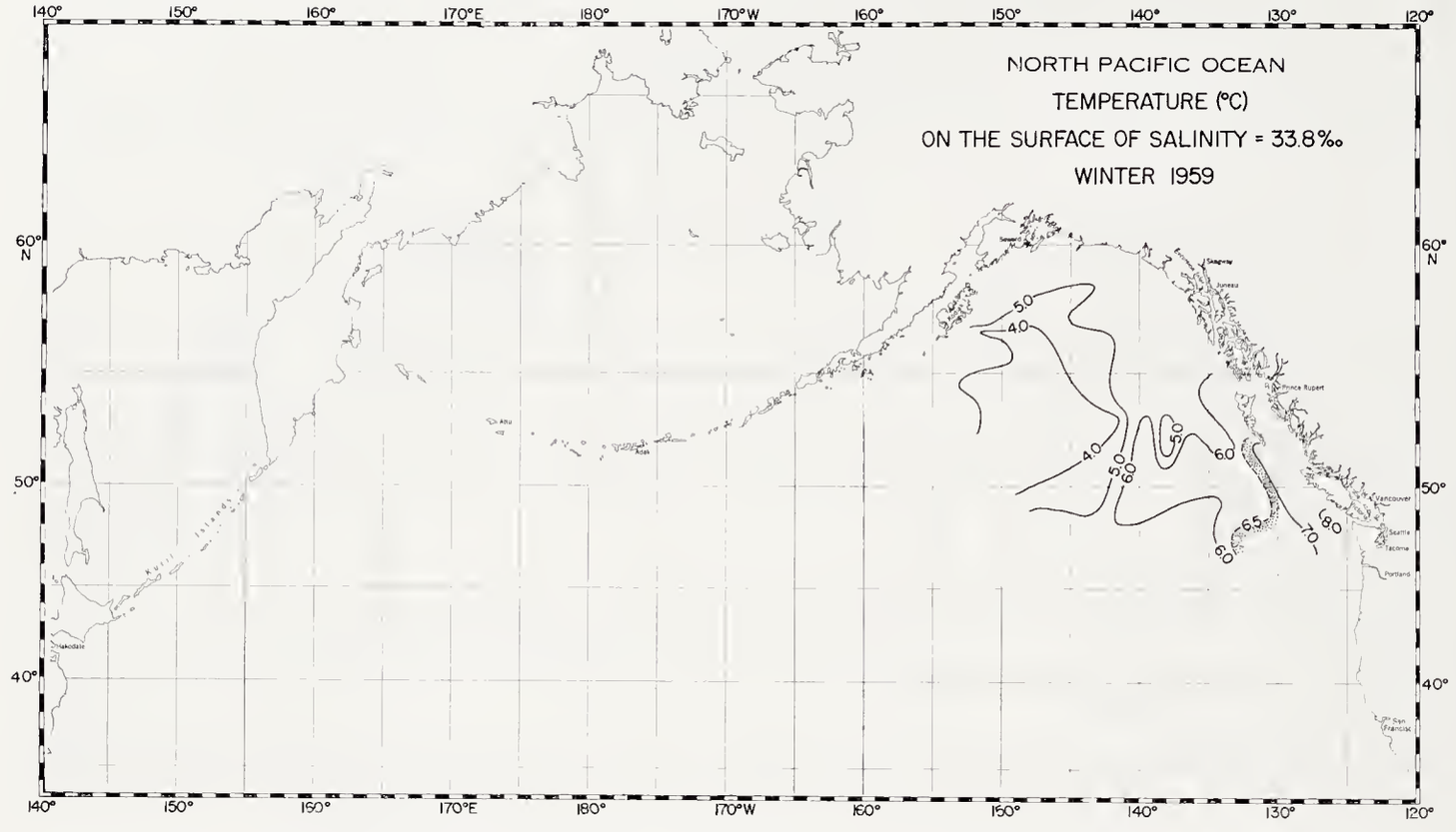


FIGURE 197. Temperature on the surface of salinity=33.8‰, winter 1959.

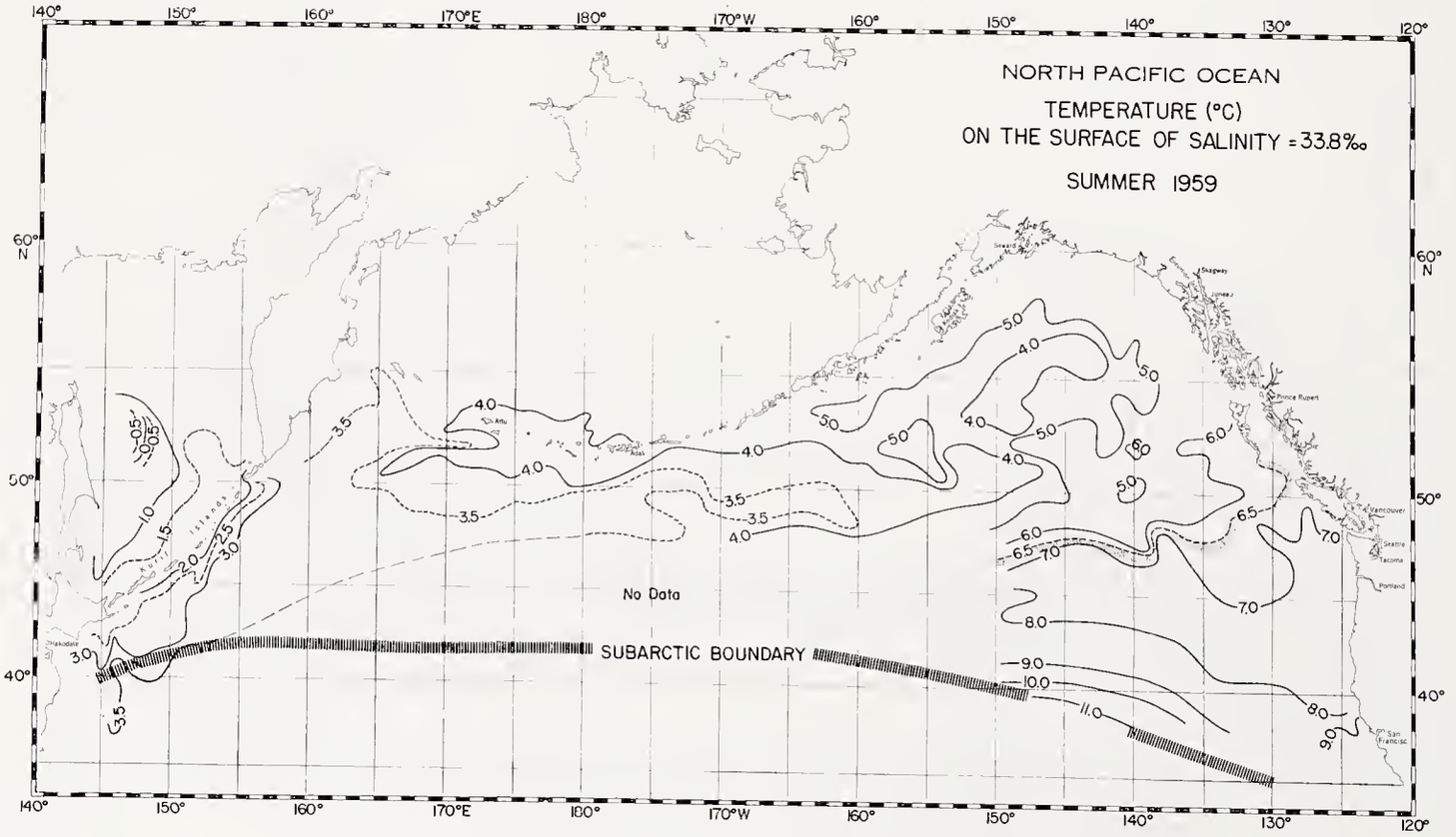


FIGURE 198. Temperature on the surface of salinity=33.8‰, summer 1959.

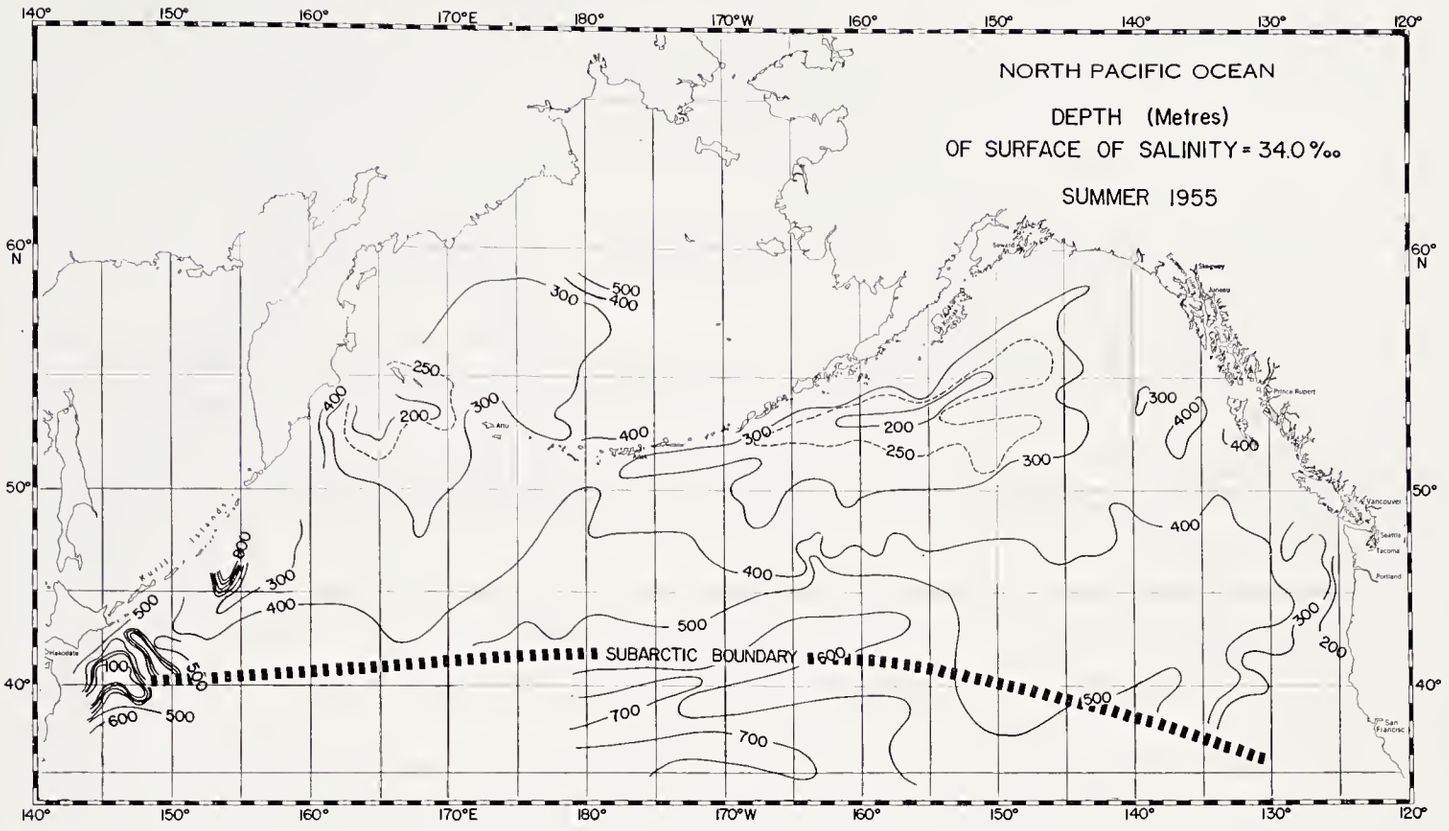


FIGURE 199. Depth (metres) of surface of salinity=34.0‰, summer 1955.

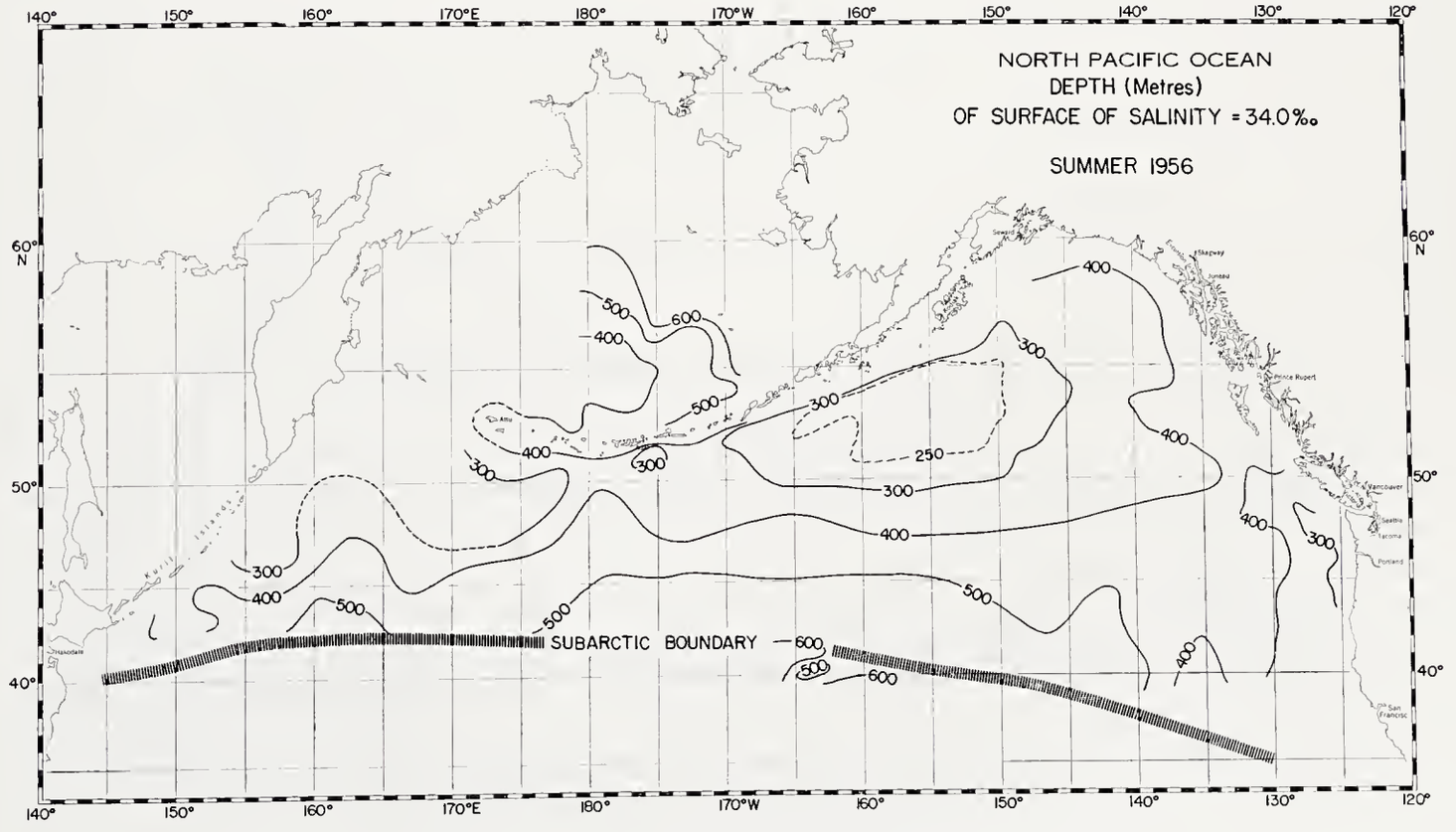


FIGURE 200. Depth (metres) of surface of salinity=34.0‰, summer 1956.

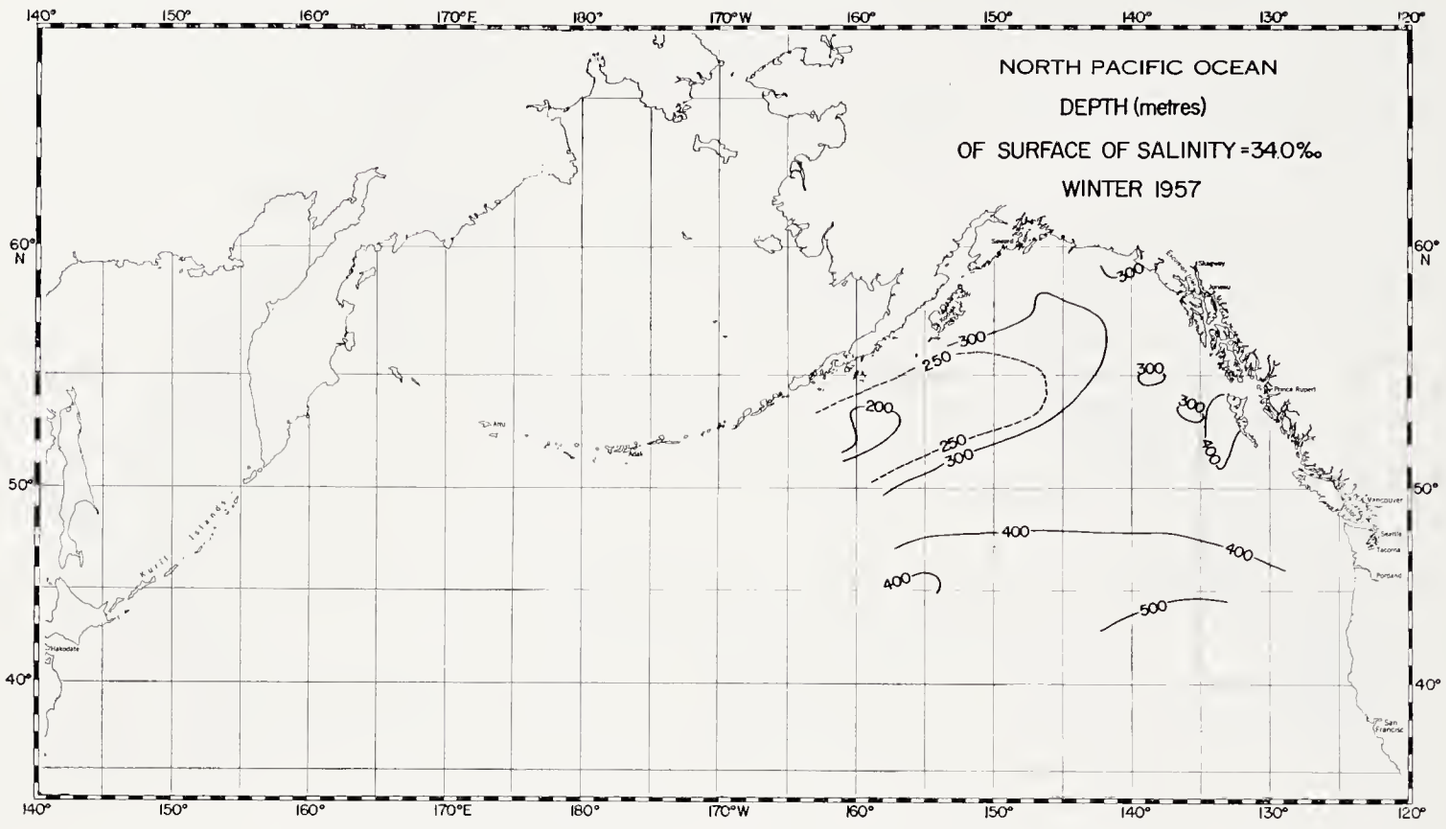


FIGURE 201. Depth (metres) of surface of salinity=34.0‰, winter 1957.

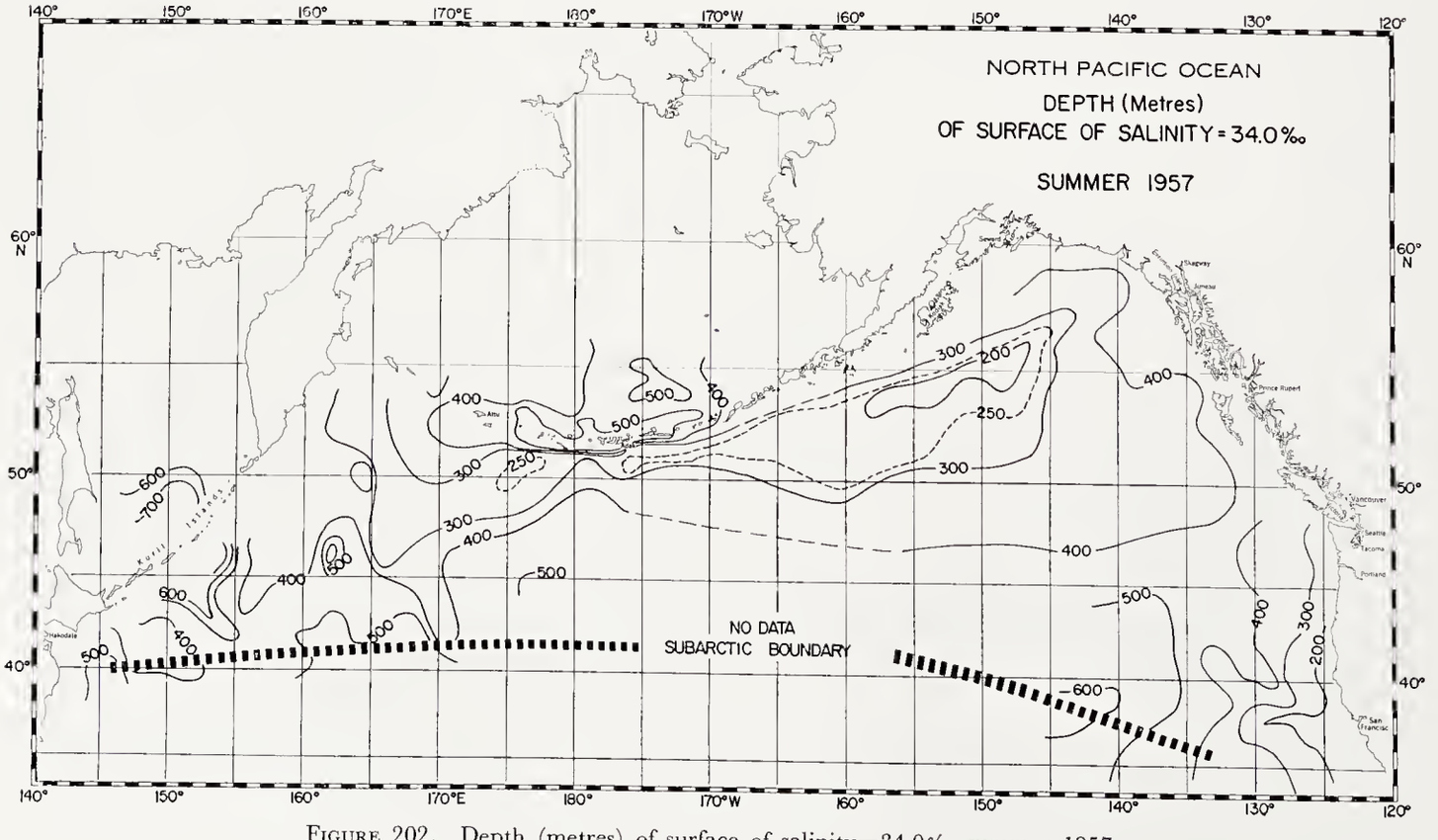


FIGURE 202. Depth (metres) of surface of salinity=34.0‰, summer 1957.

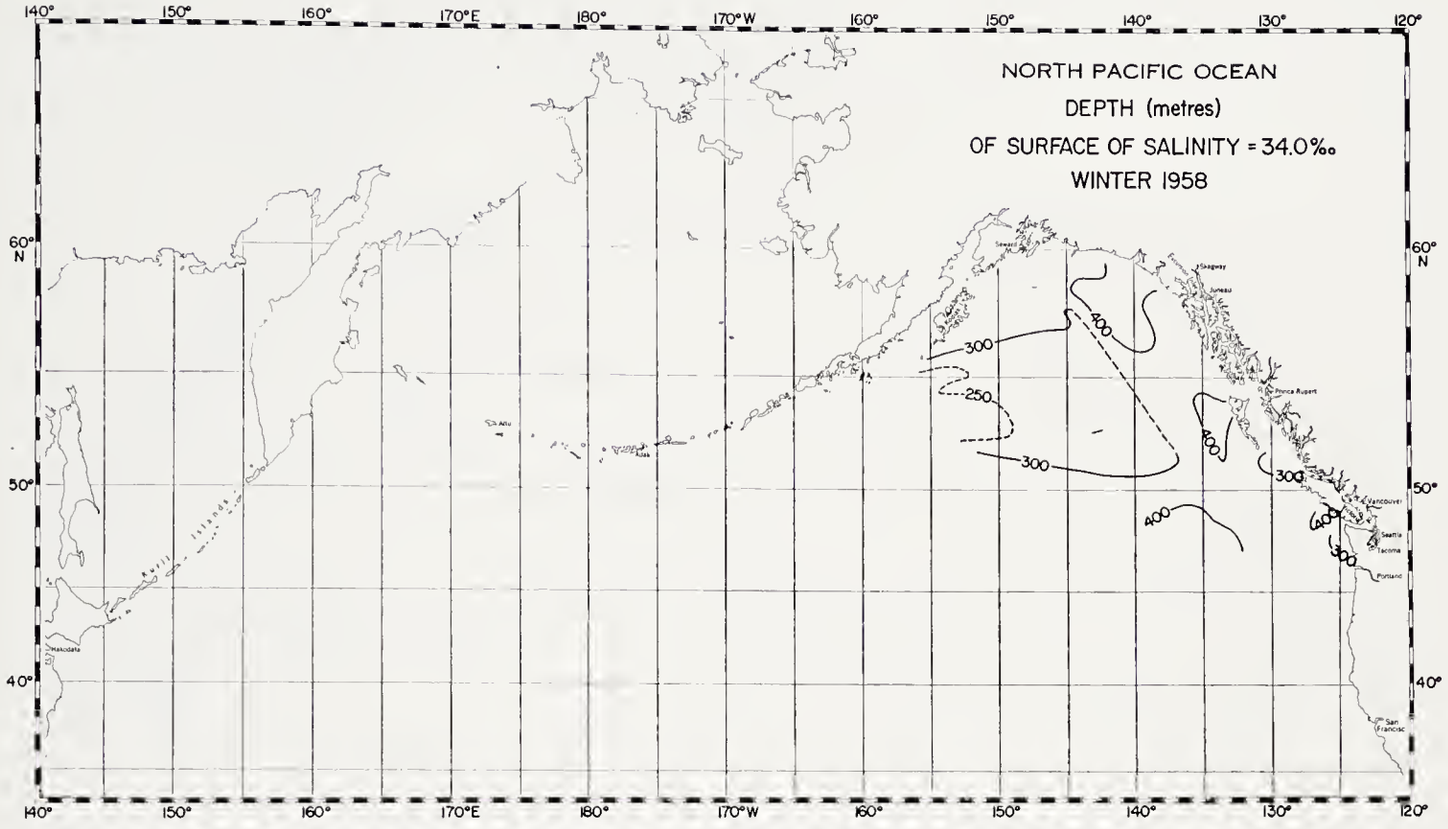


FIGURE 203. Depth (metres) of surface of salinity=34.0‰, winter 1958.

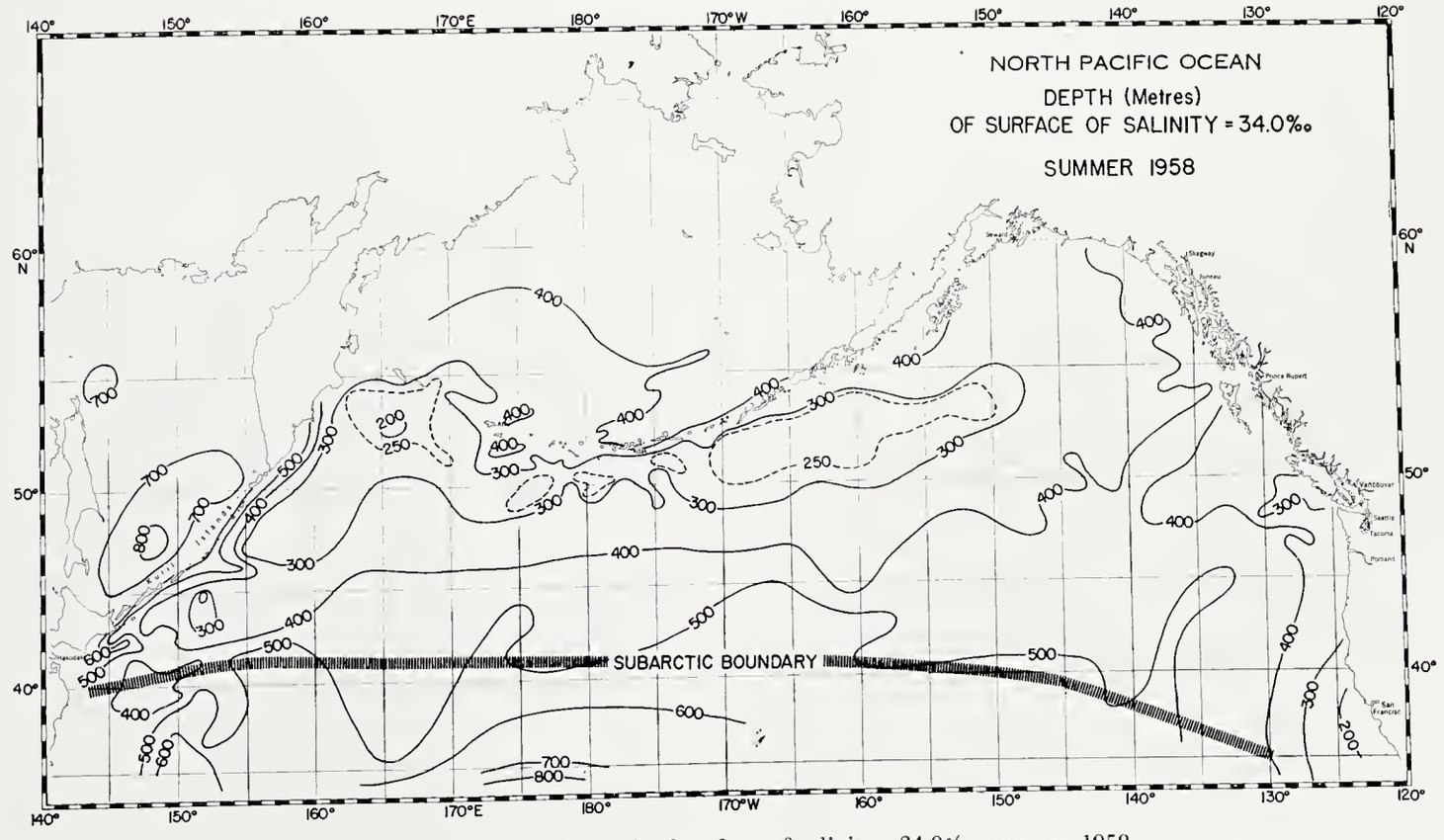


FIGURE 204. Depth (metres) of surface of salinity=34.0‰, summer 1958.

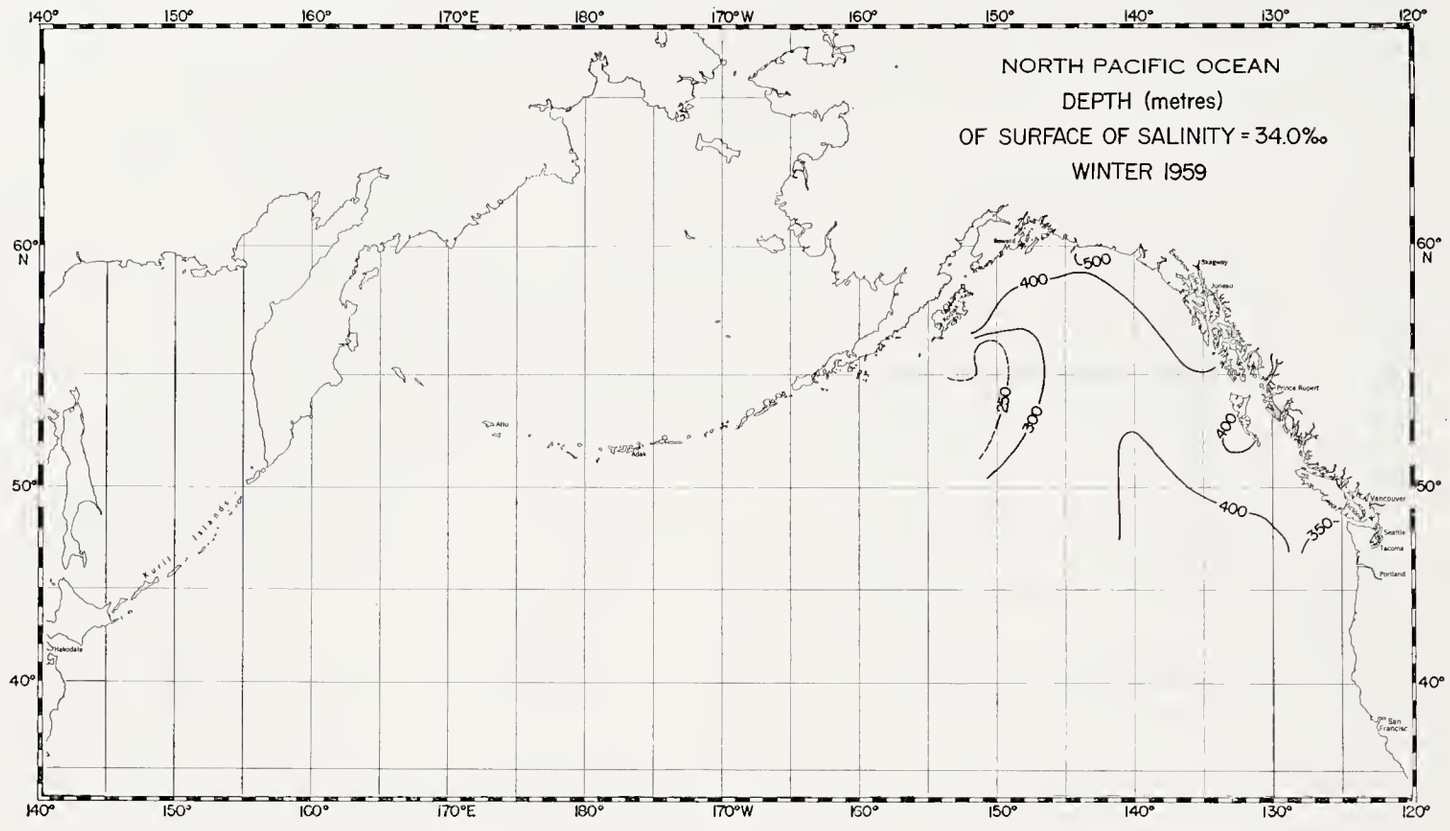


FIGURE 205. Depth (metres) of surface of salinity=34.0‰, winter 1959.

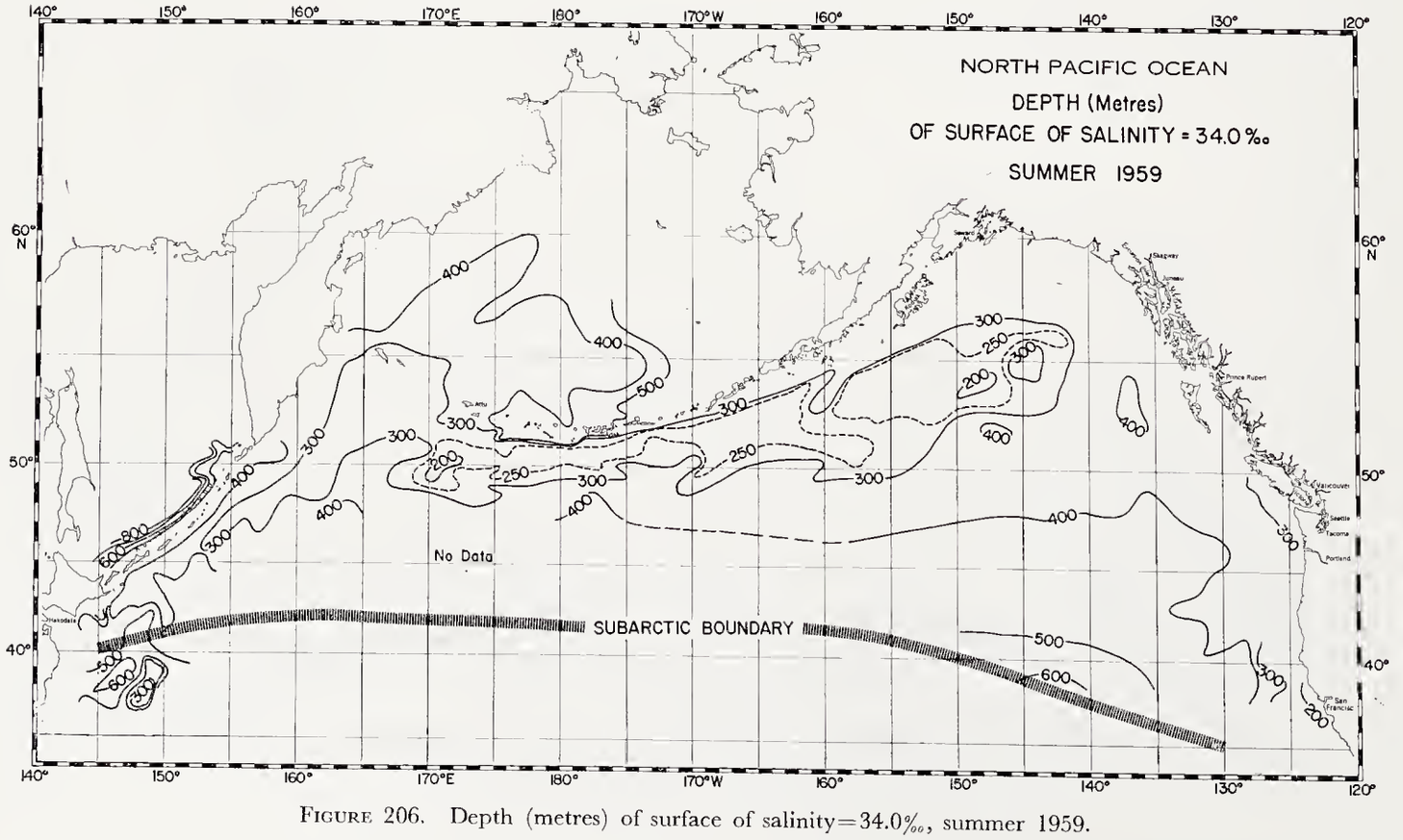


FIGURE 206. Depth (metres) of surface of salinity=34.0‰, summer 1959.

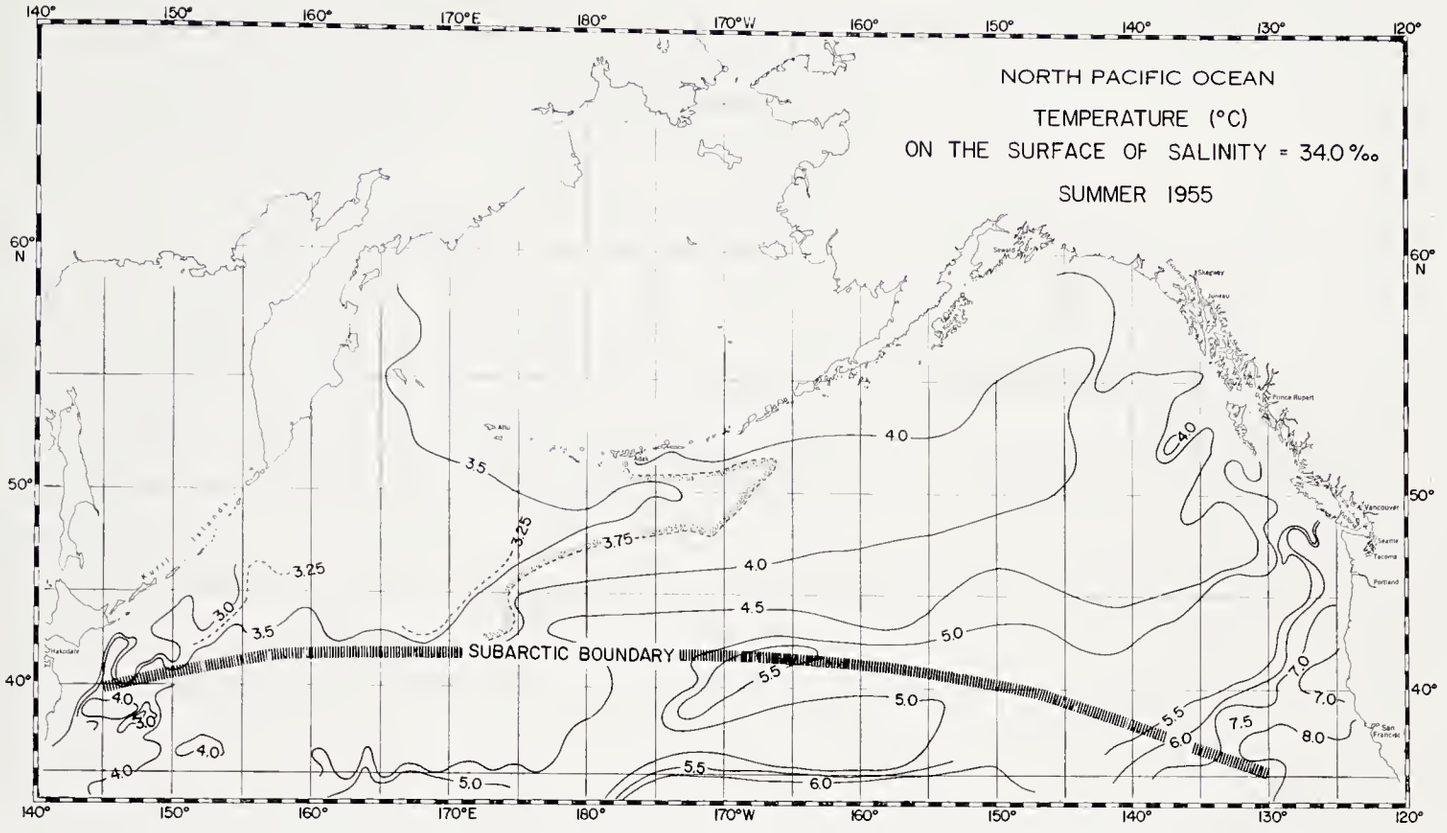


FIGURE 207. Temperature on the surface of salinity=34.0‰, summer 1955.

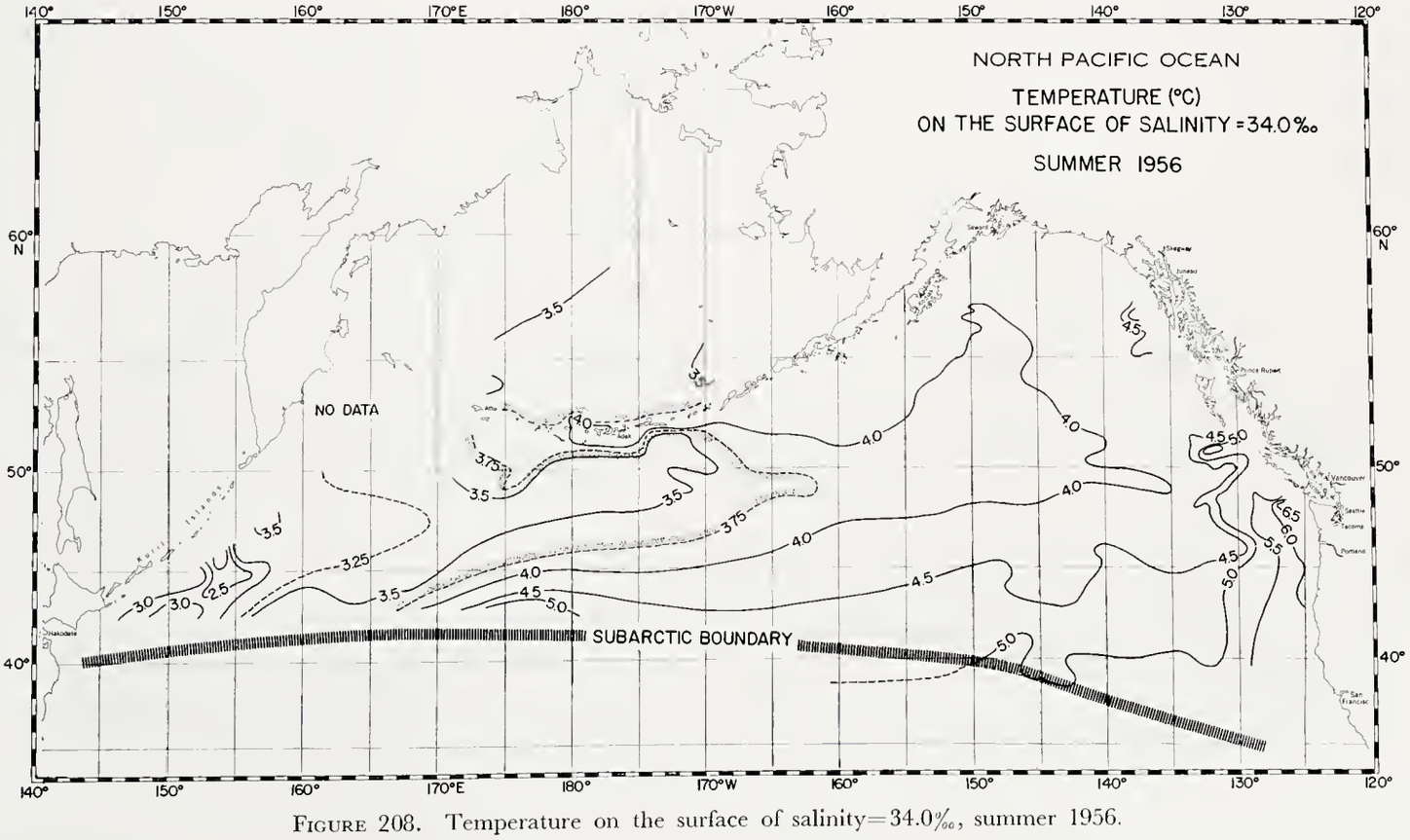


FIGURE 208. Temperature on the surface of salinity=34.0‰, summer 1956.

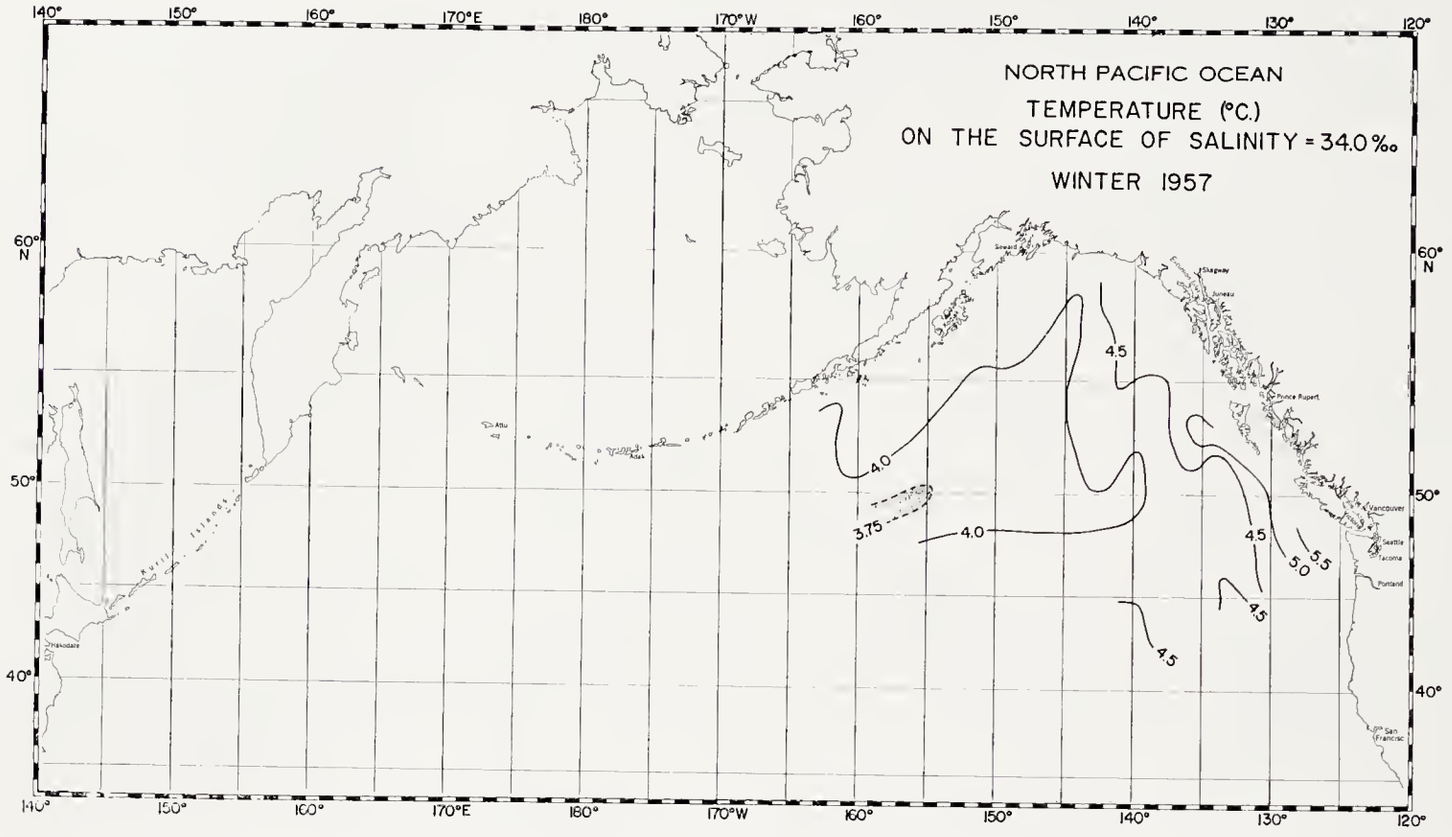


FIGURE 209. Temperature on the surface of salinity=34.0‰, winter 1957.

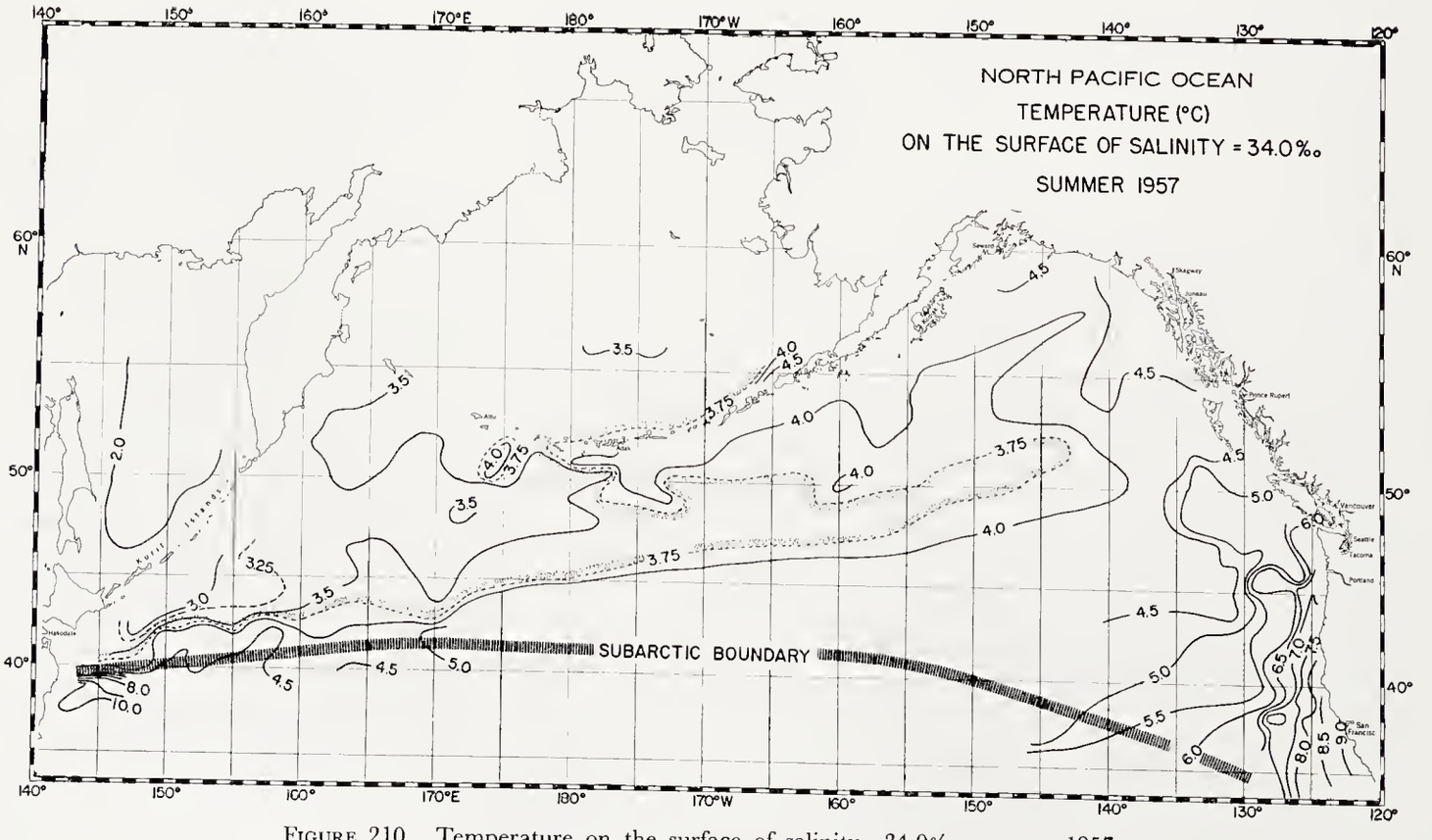


FIGURE 210. Temperature on the surface of salinity=34.0‰, summer 1957.

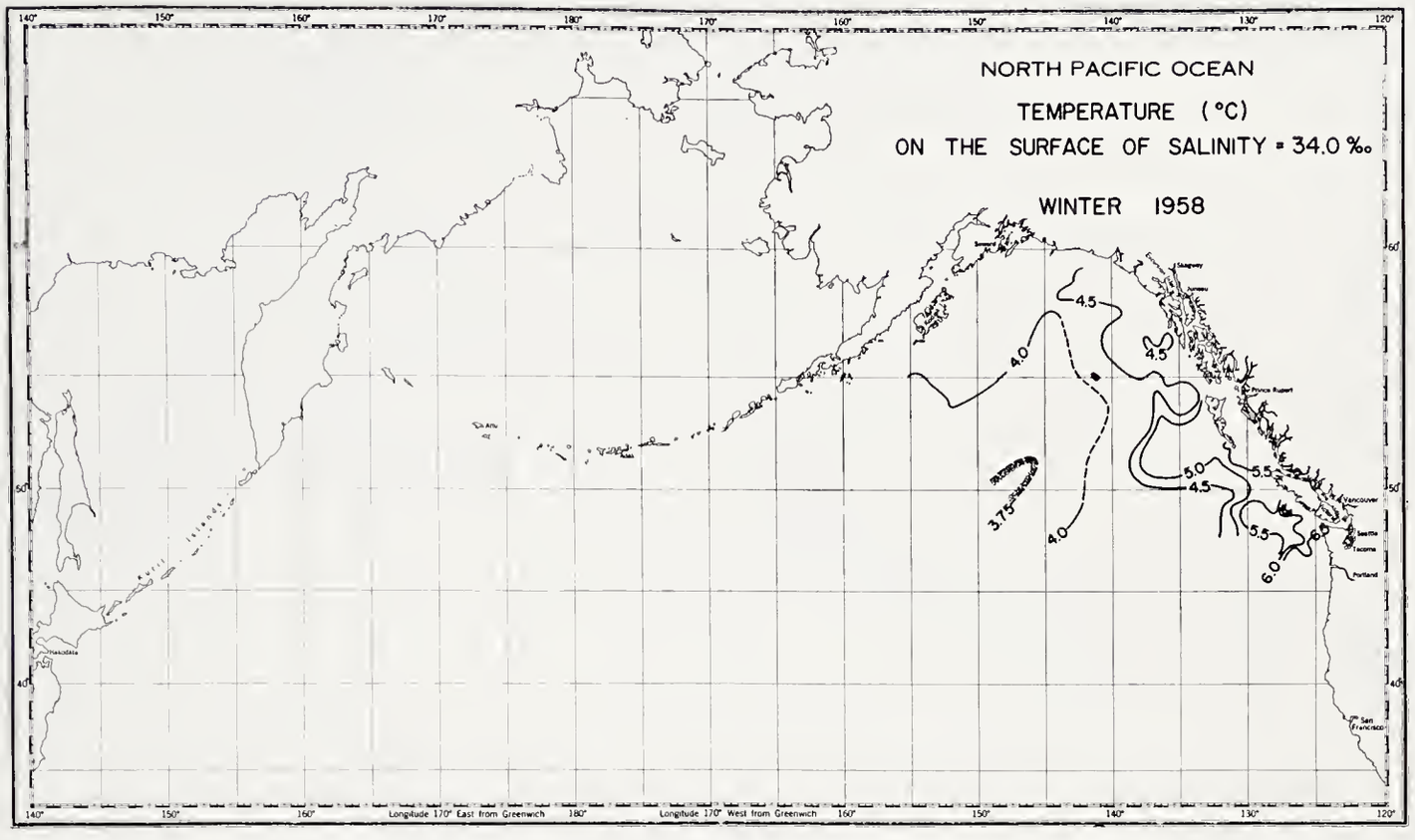

NORTH PACIFIC OCEAN
TEMPERATURE (°C)
ON THE SURFACE OF SALINITY = 34.0 ‰
WINTER 1958
Longitude 170° East from Greenwich
Longitude 170° West from Greenwich

FIGURE 211. Temperature on the surface of salinity=34.0‰, winter 1958.

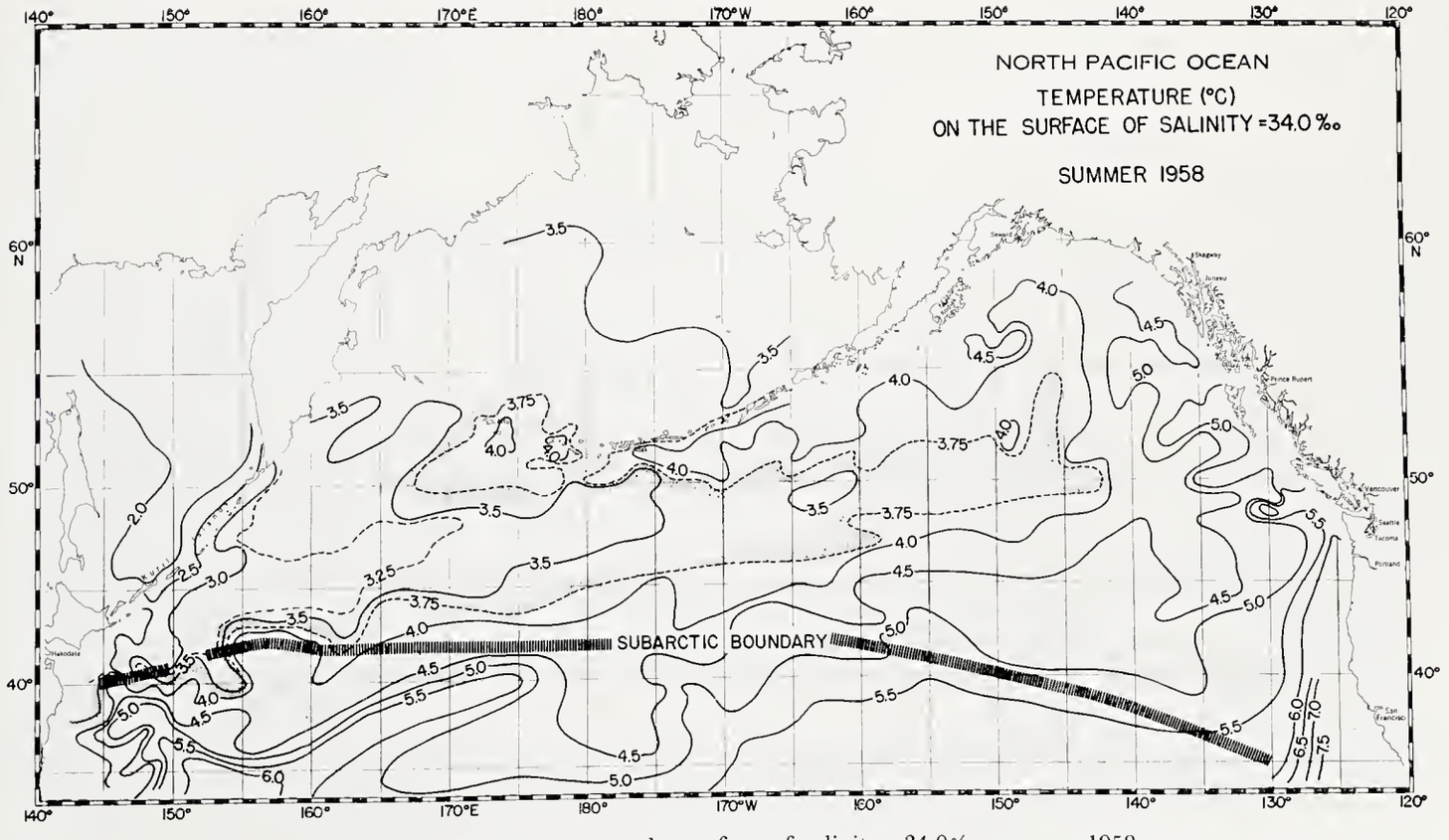


FIGURE 212. Temperature on the surface of salinity=34.0‰, summer 1958.

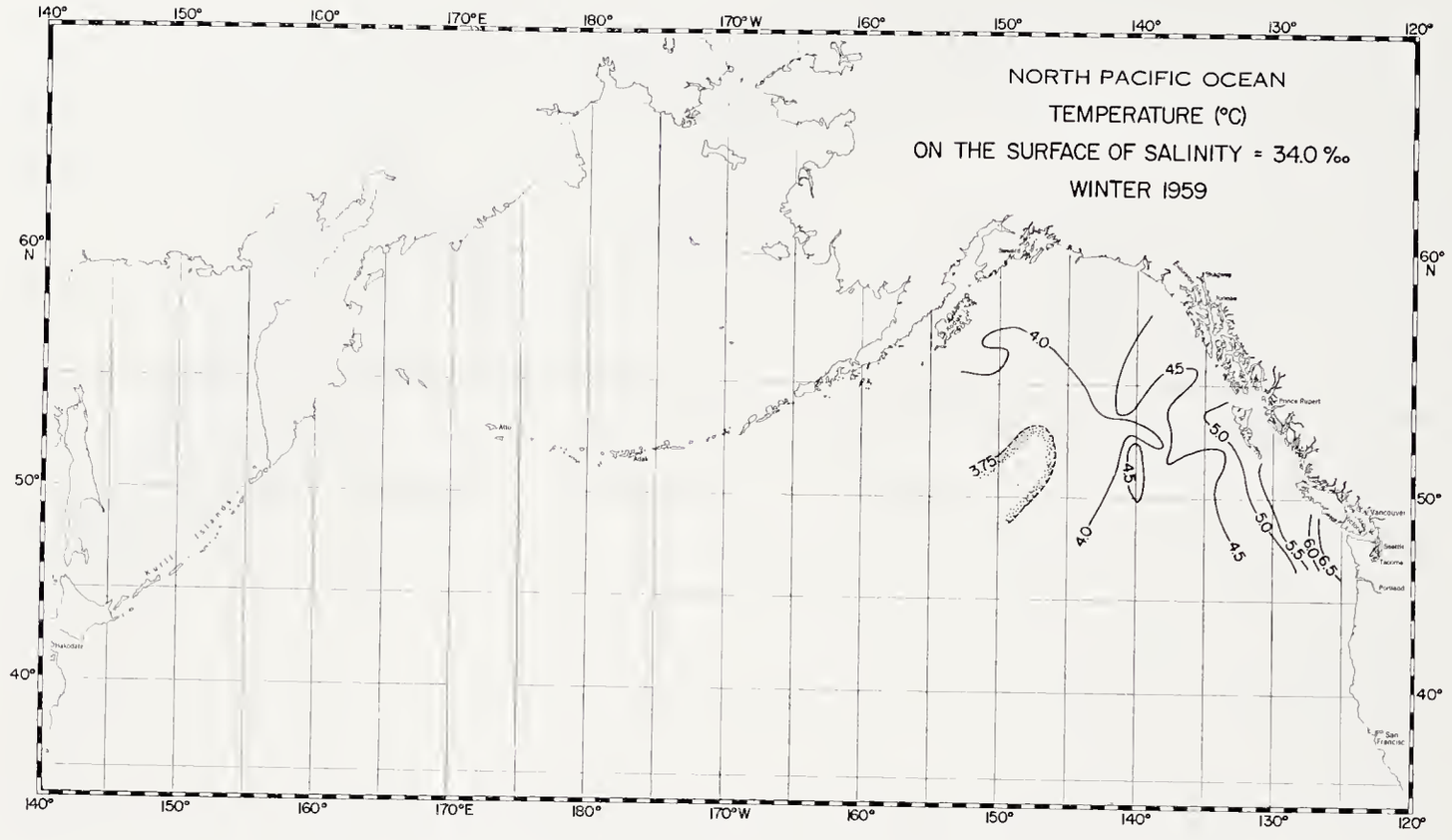


FIGURE 213. Temperature on the surface of salinity=34.0‰, winter 1959.

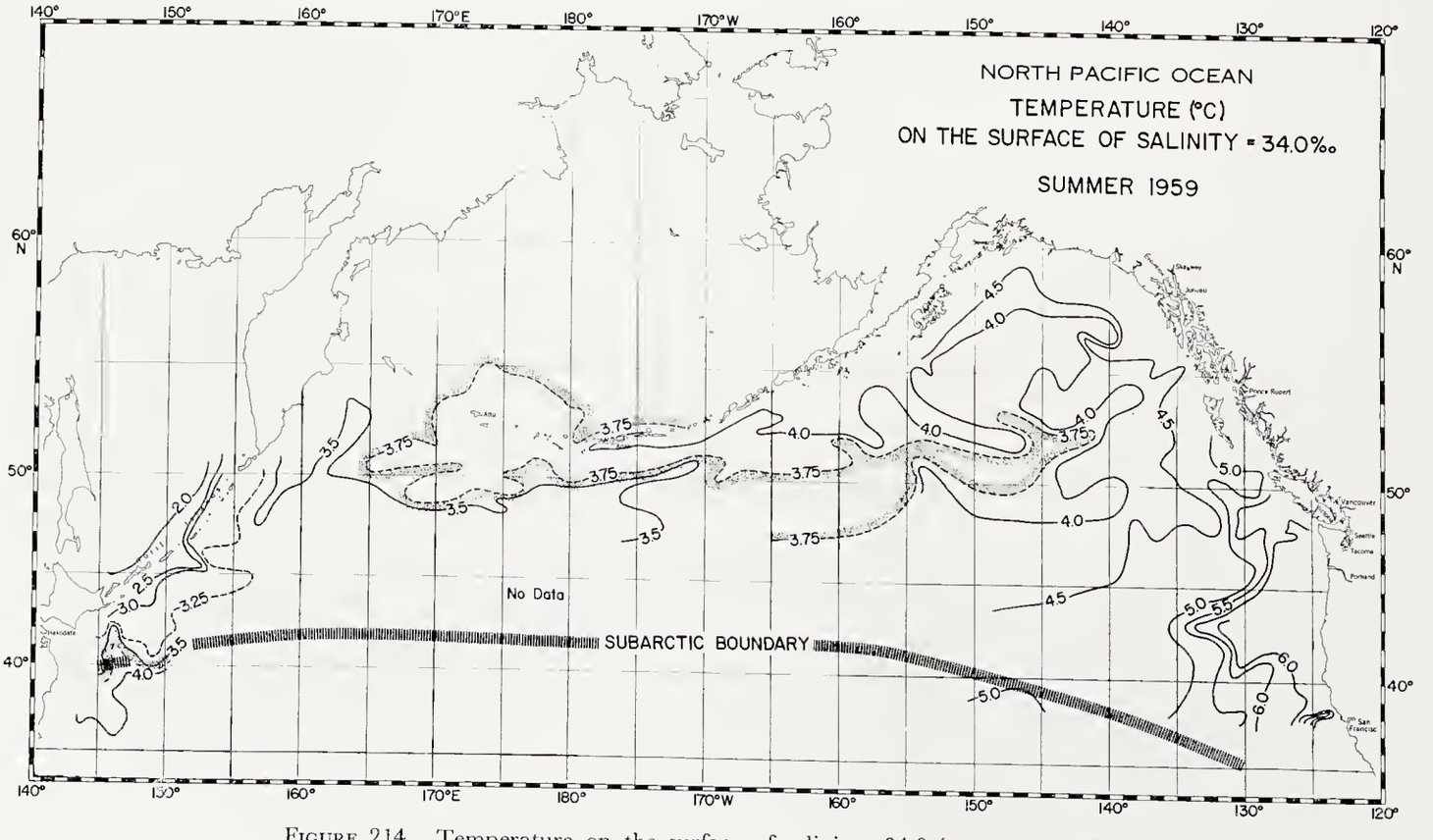


FIGURE 214. Temperature on the surface of salinity=34.0‰, summer 1959.

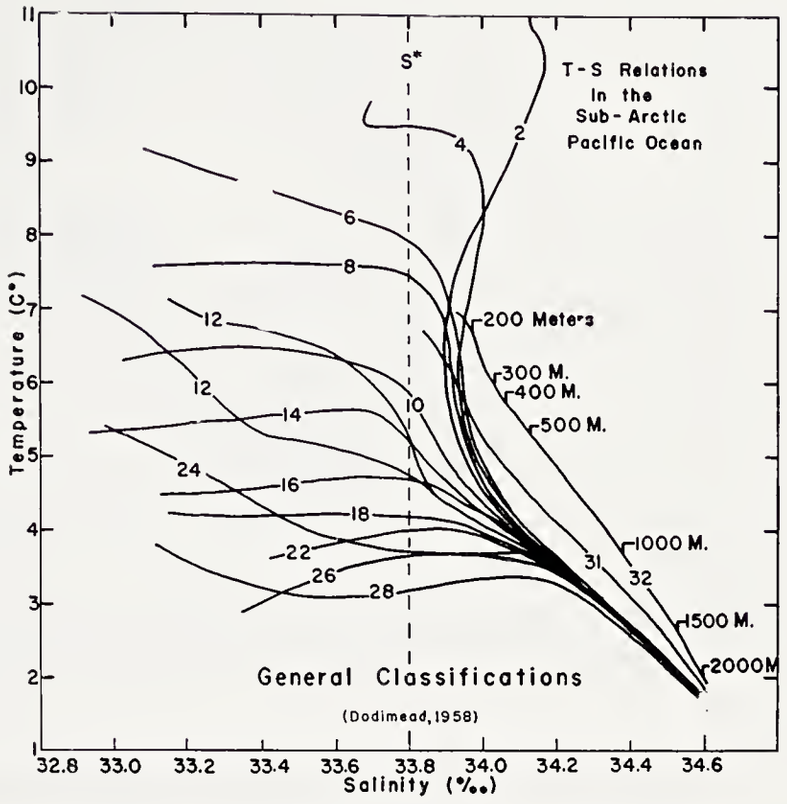


FIGURE 215. Temperature-salinity curves (Dodimead, 1958).

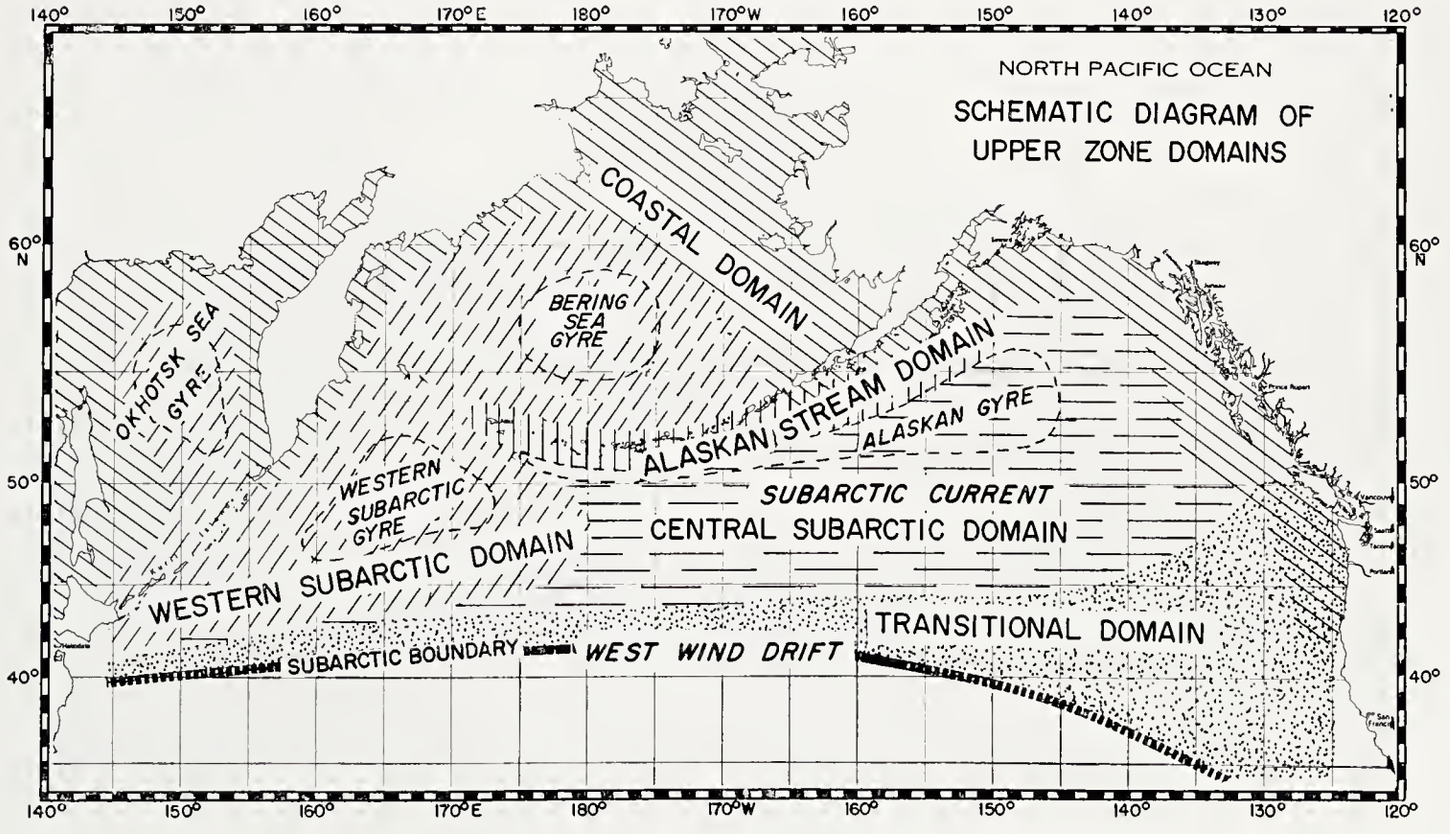


FIGURE 216. Schematic diagram of upper zone domains.

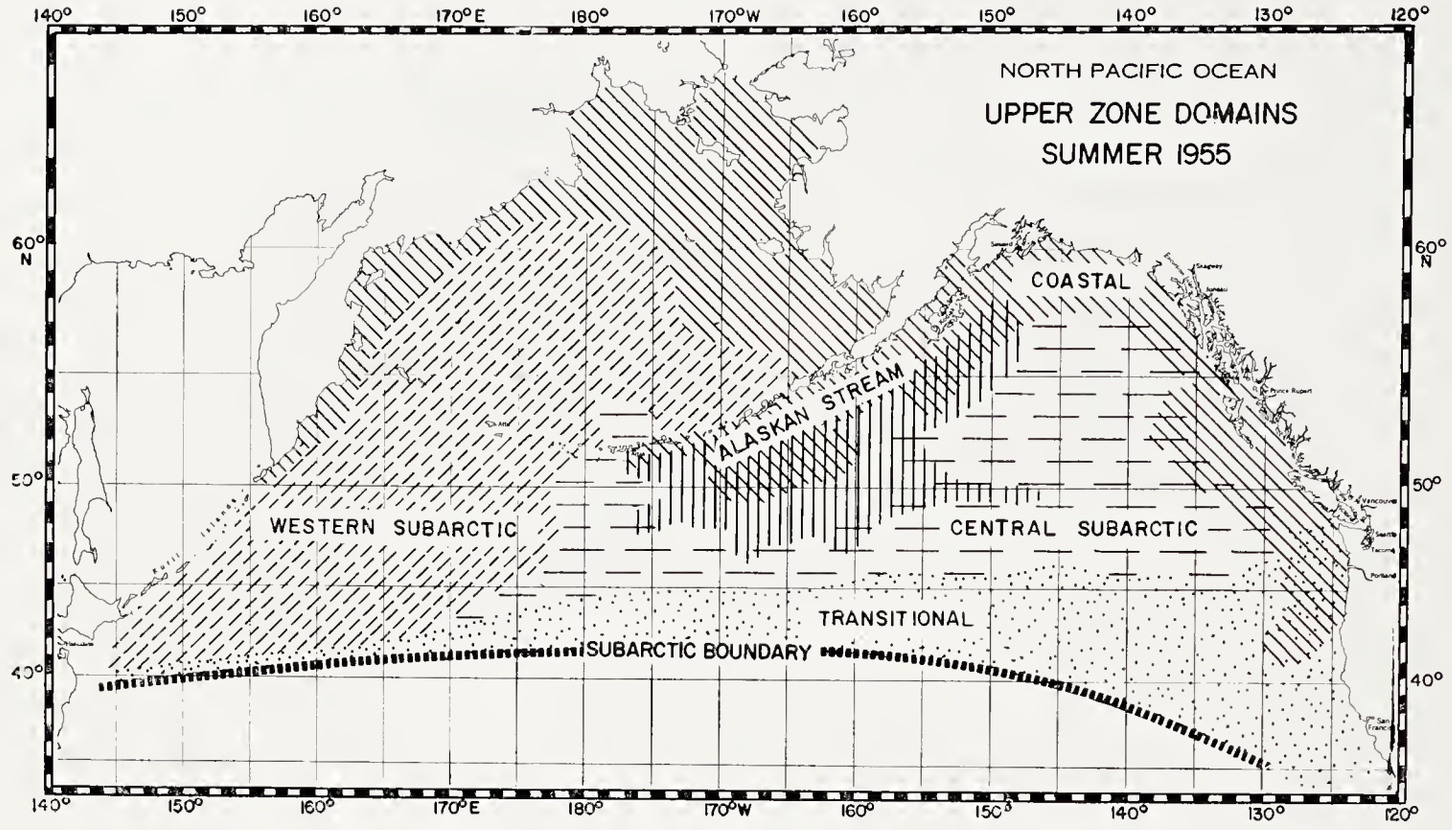


FIGURE 217. Upper zone domains, summer 1955.

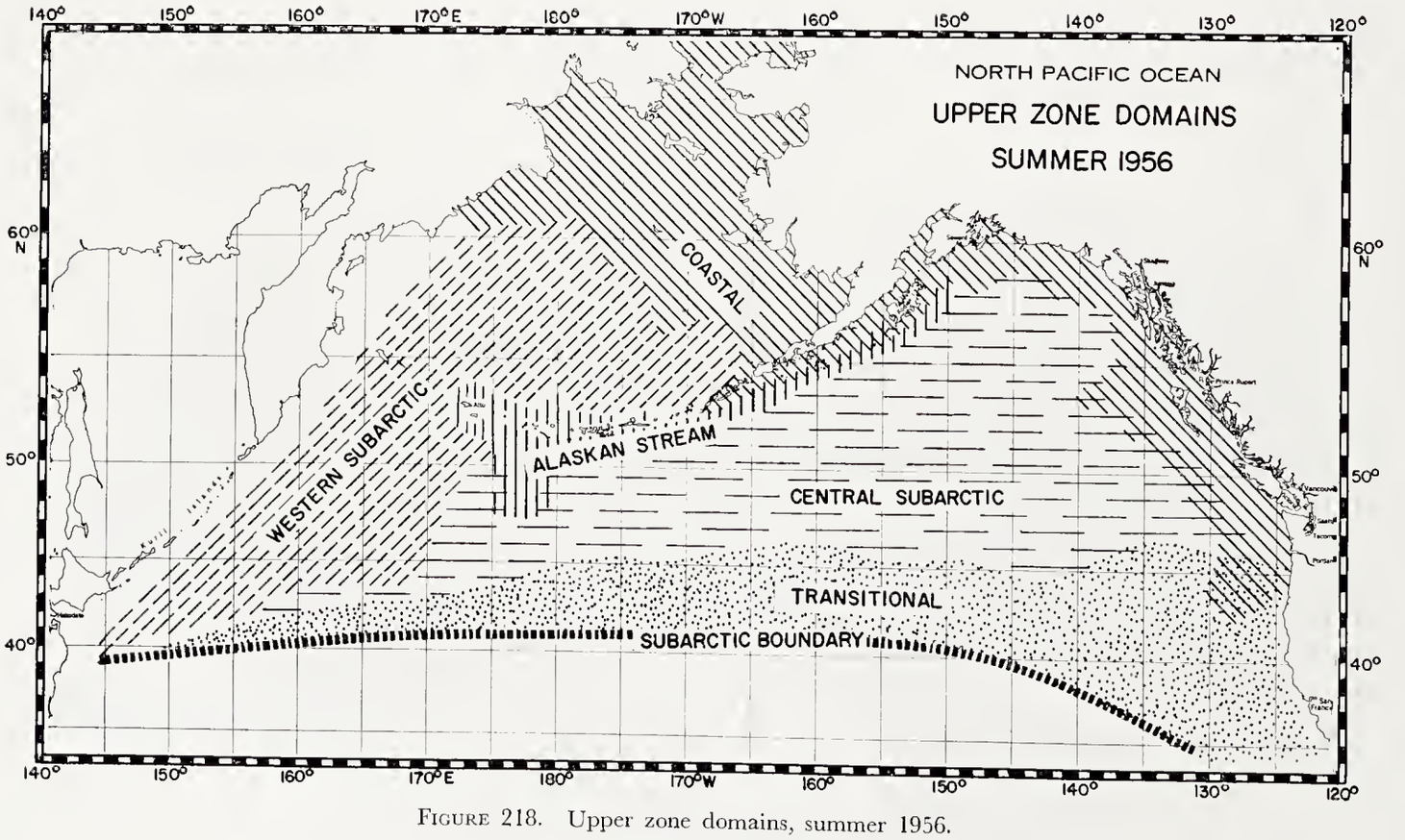


FIGURE 218. Upper zone domains, summer 1956.

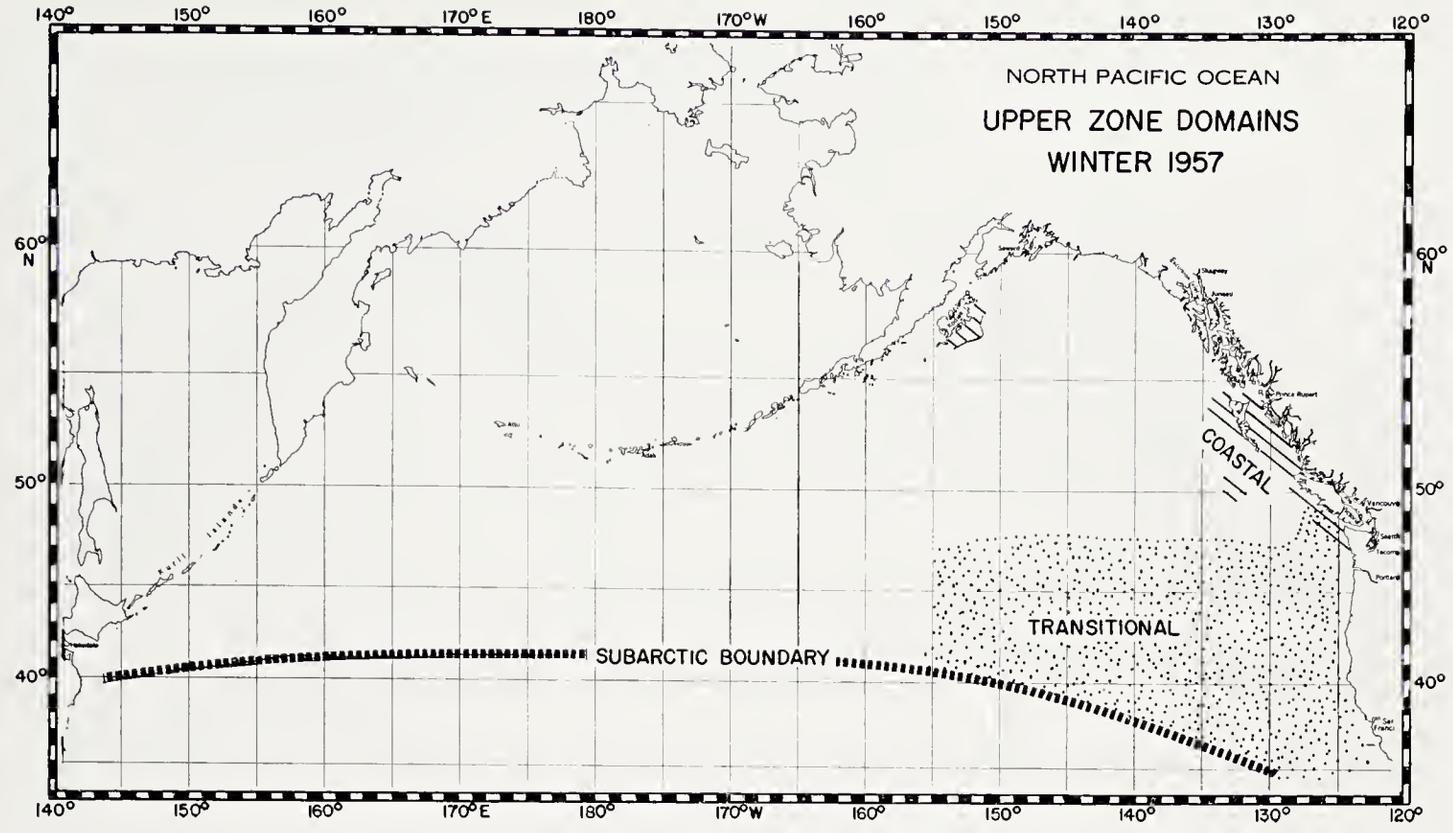


FIGURE 219. Upper zone domains, winter 1957.

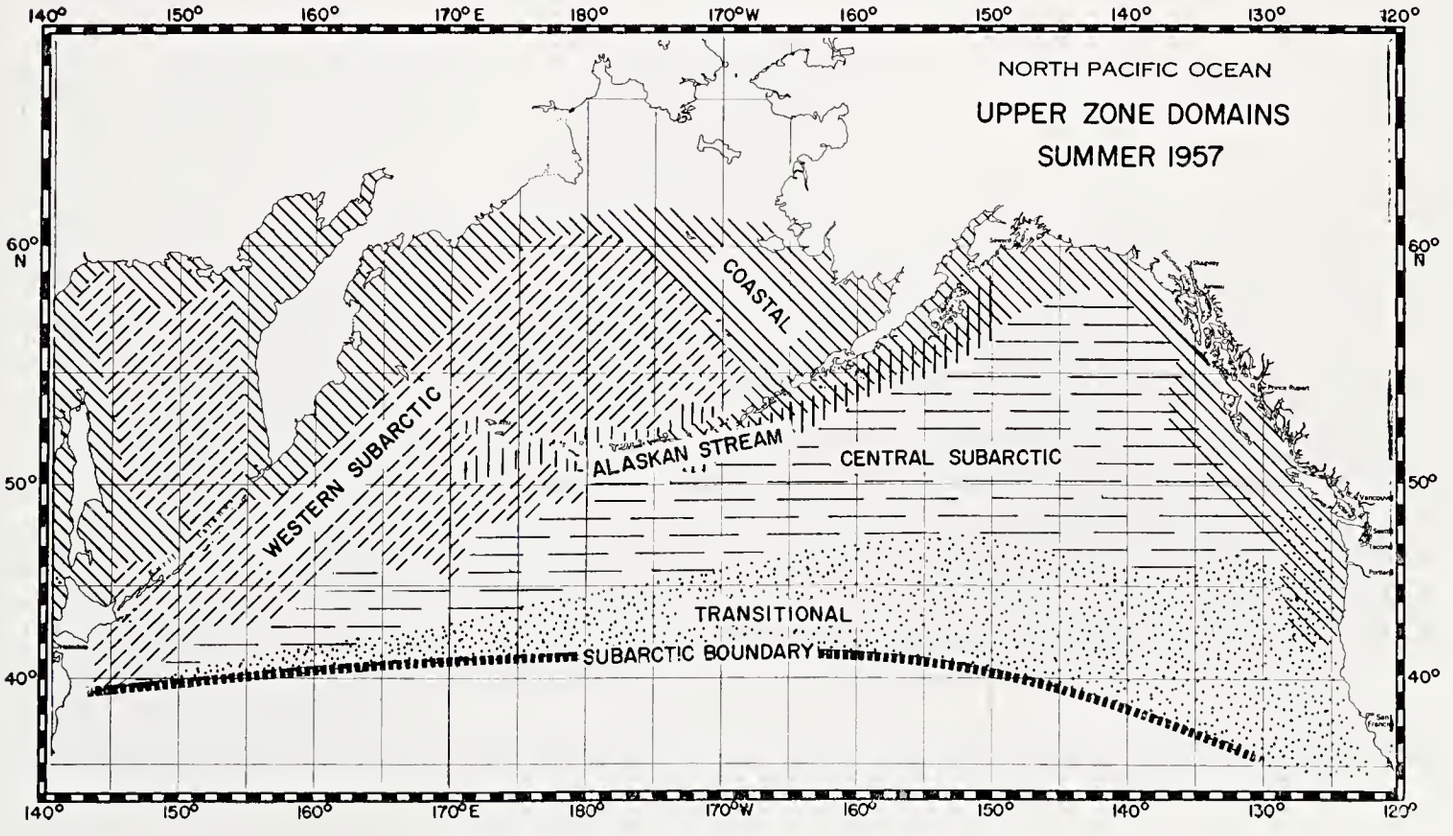


FIGURE 220. Upper zone domains, summer 1957.

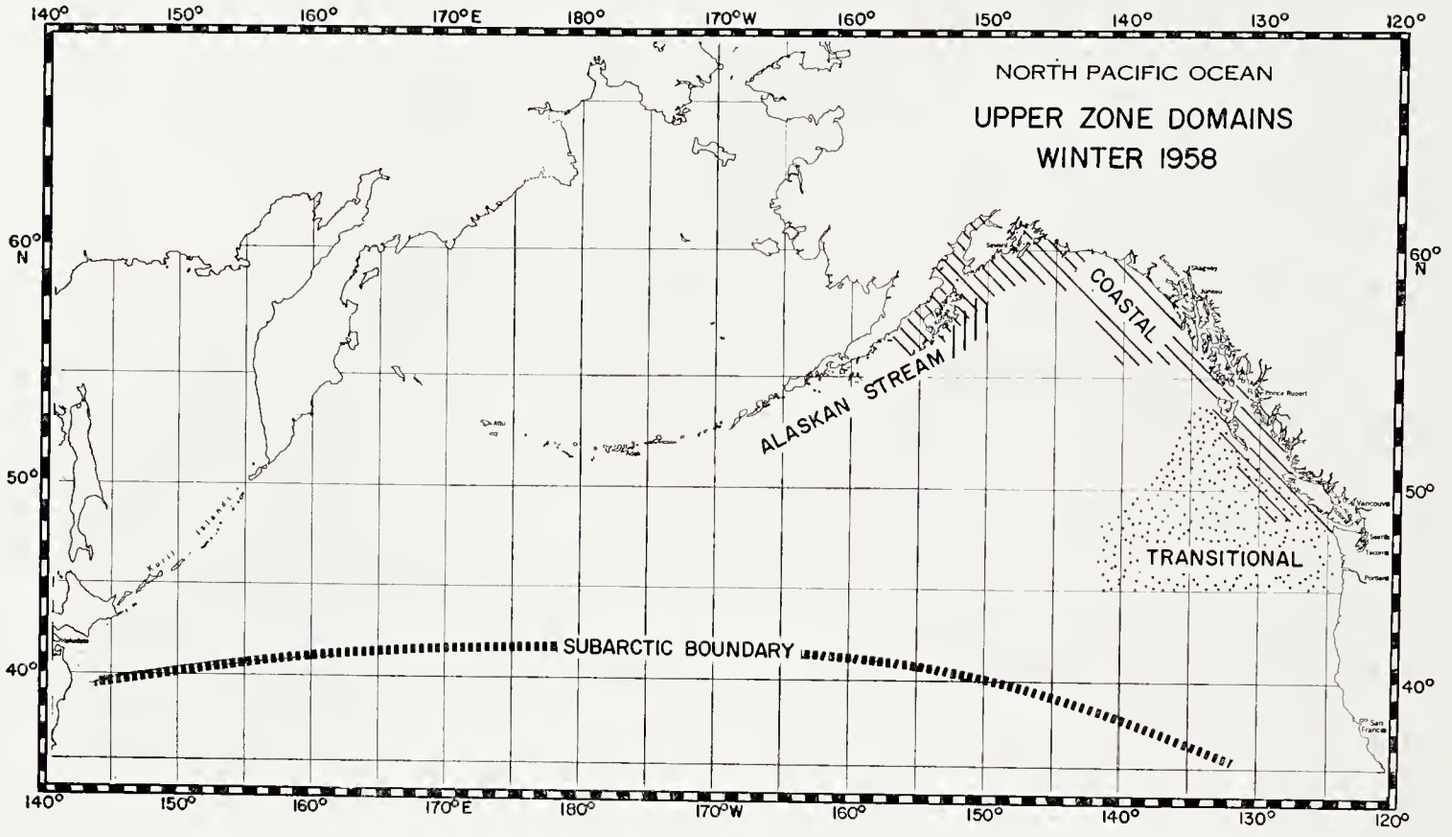


FIGURE 221. Upper zone domains, winter 1958.

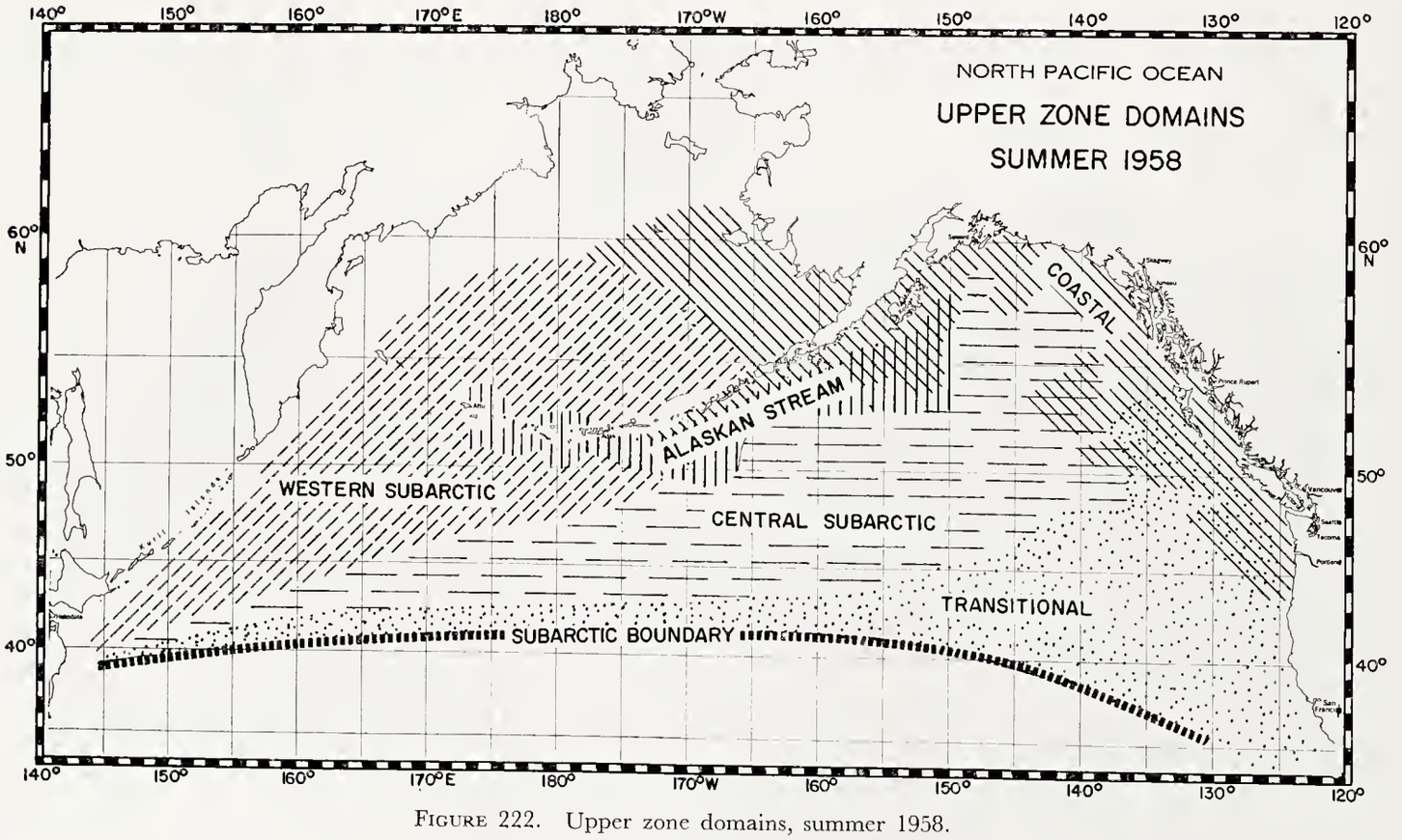


FIGURE 222. Upper zone domains, summer 1958.

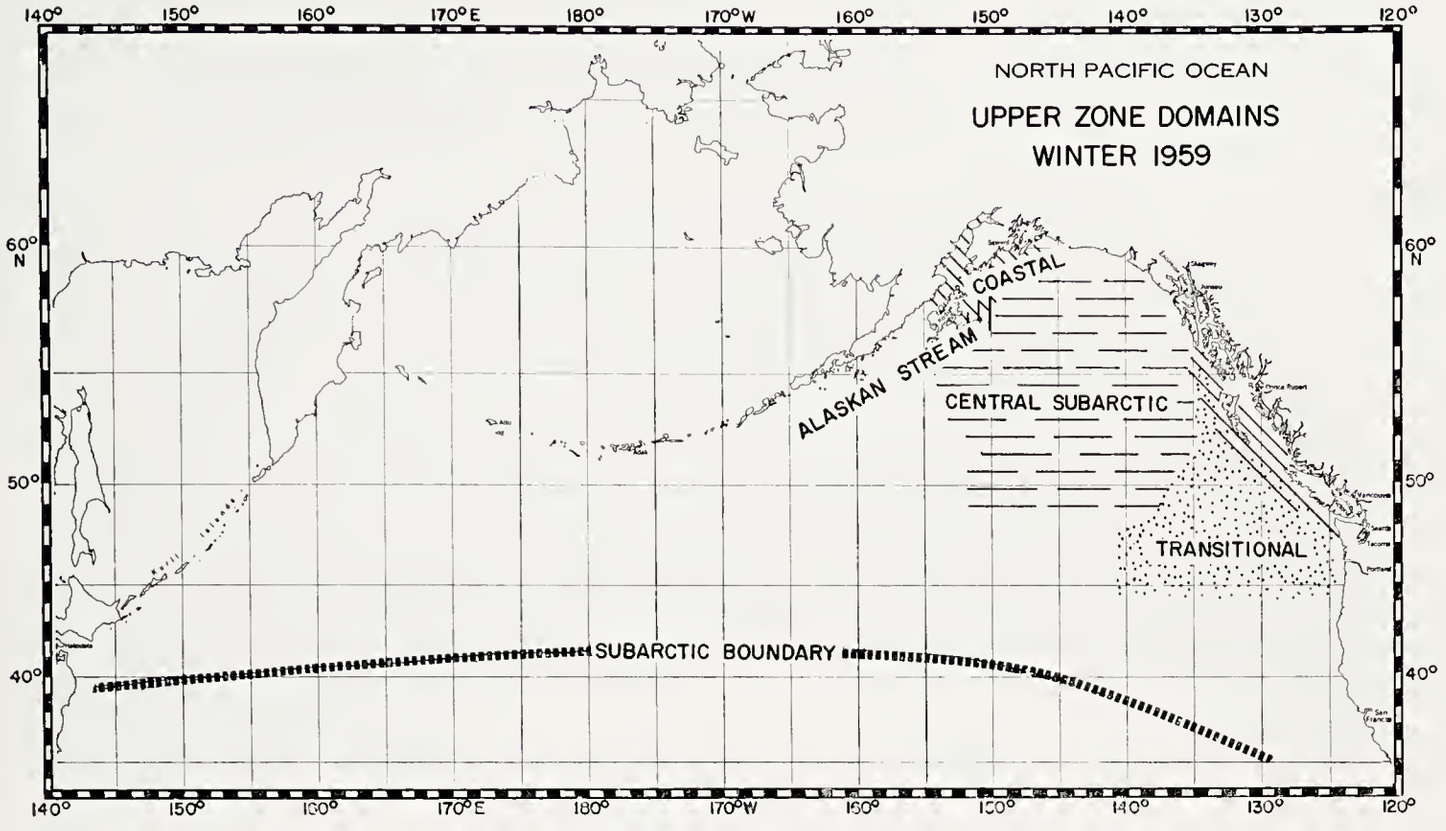


FIGURE 223. Upper zone domains, winter 1959.

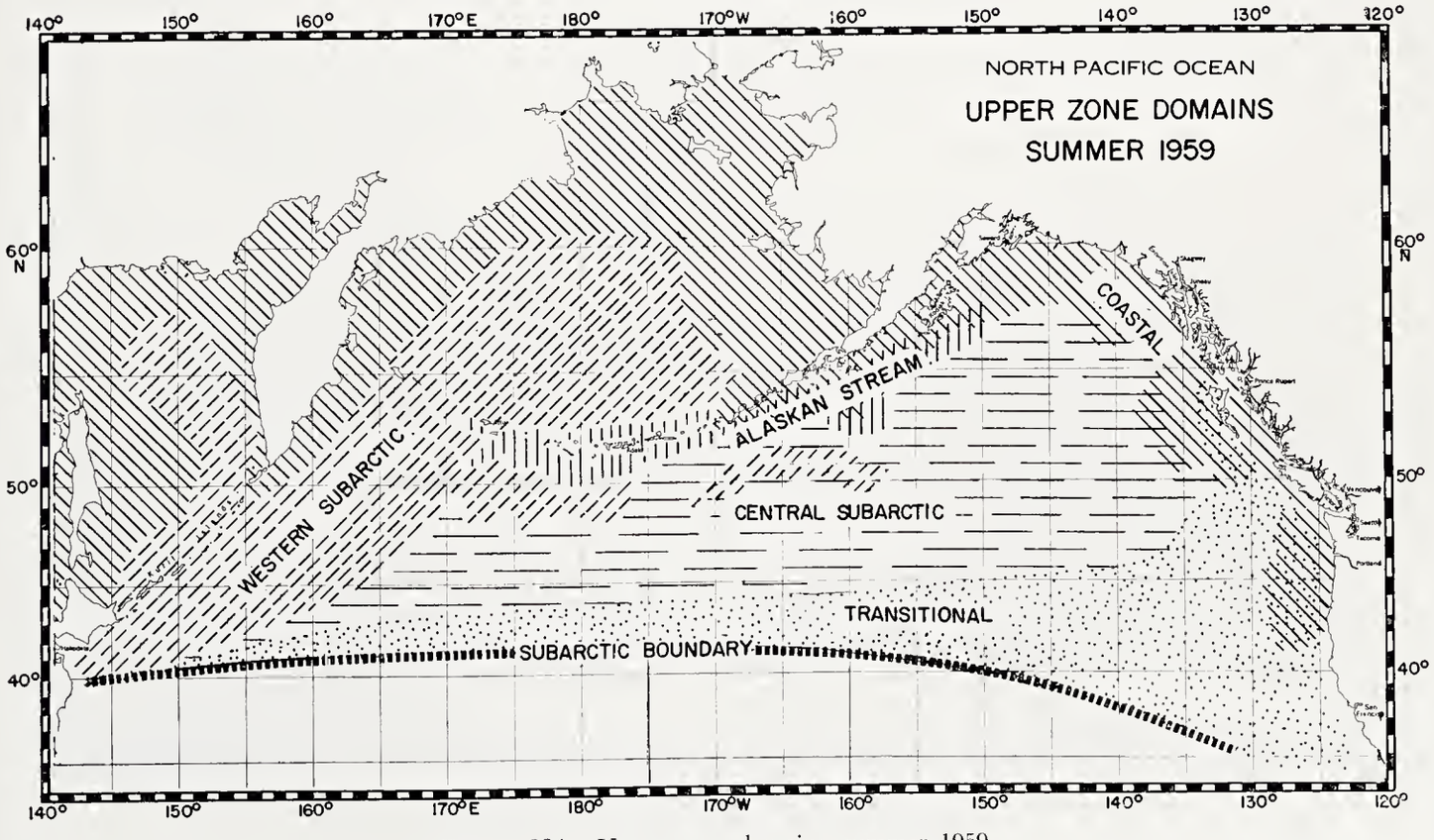


FIGURE 224. Upper zone domains, summer 1959.

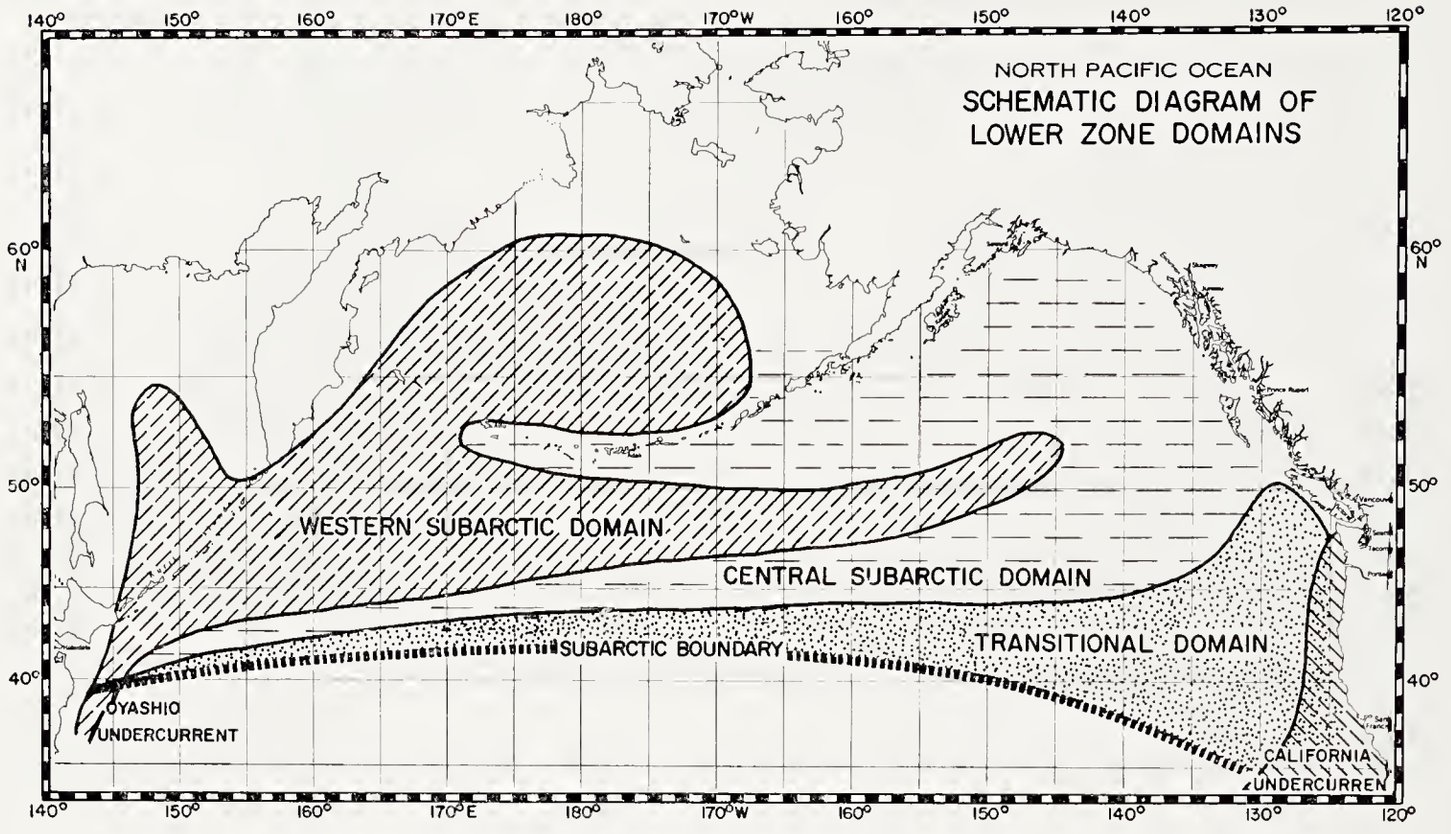


FIGURE 225. Schematic diagram of lower zone domains.

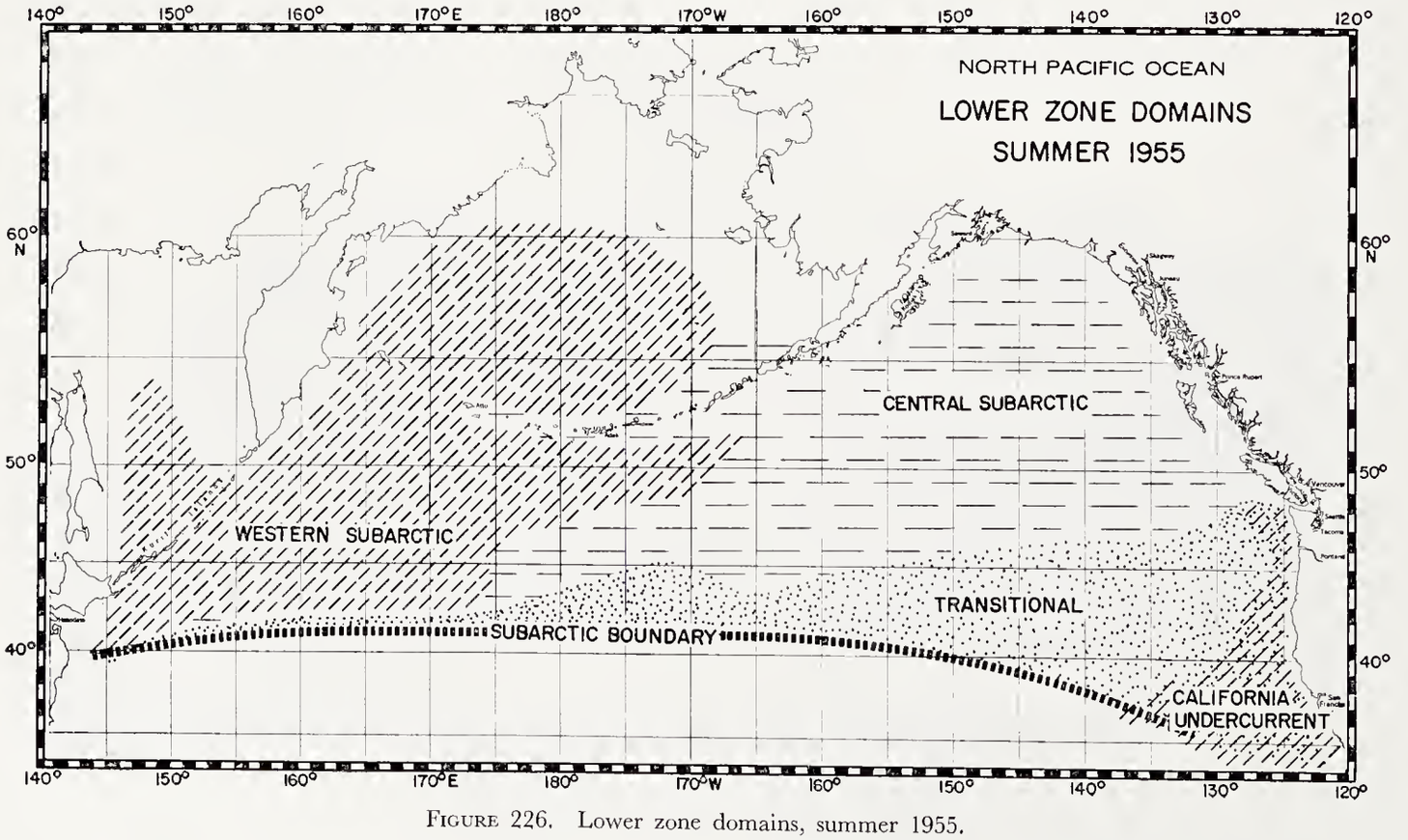


FIGURE 226. Lower zone domains, summer 1955.

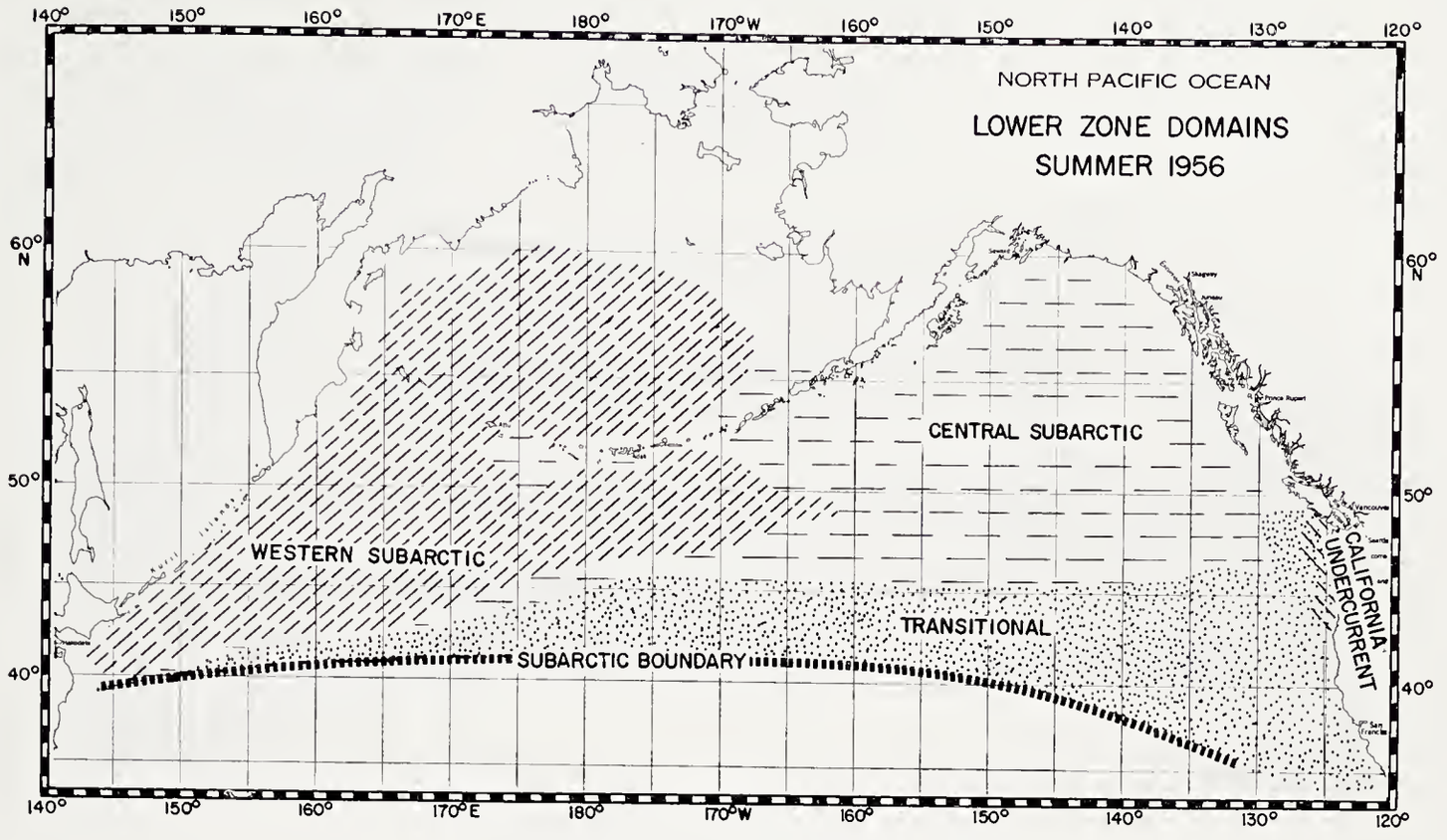


FIGURE 227. Lower zone domains, summer 1956.

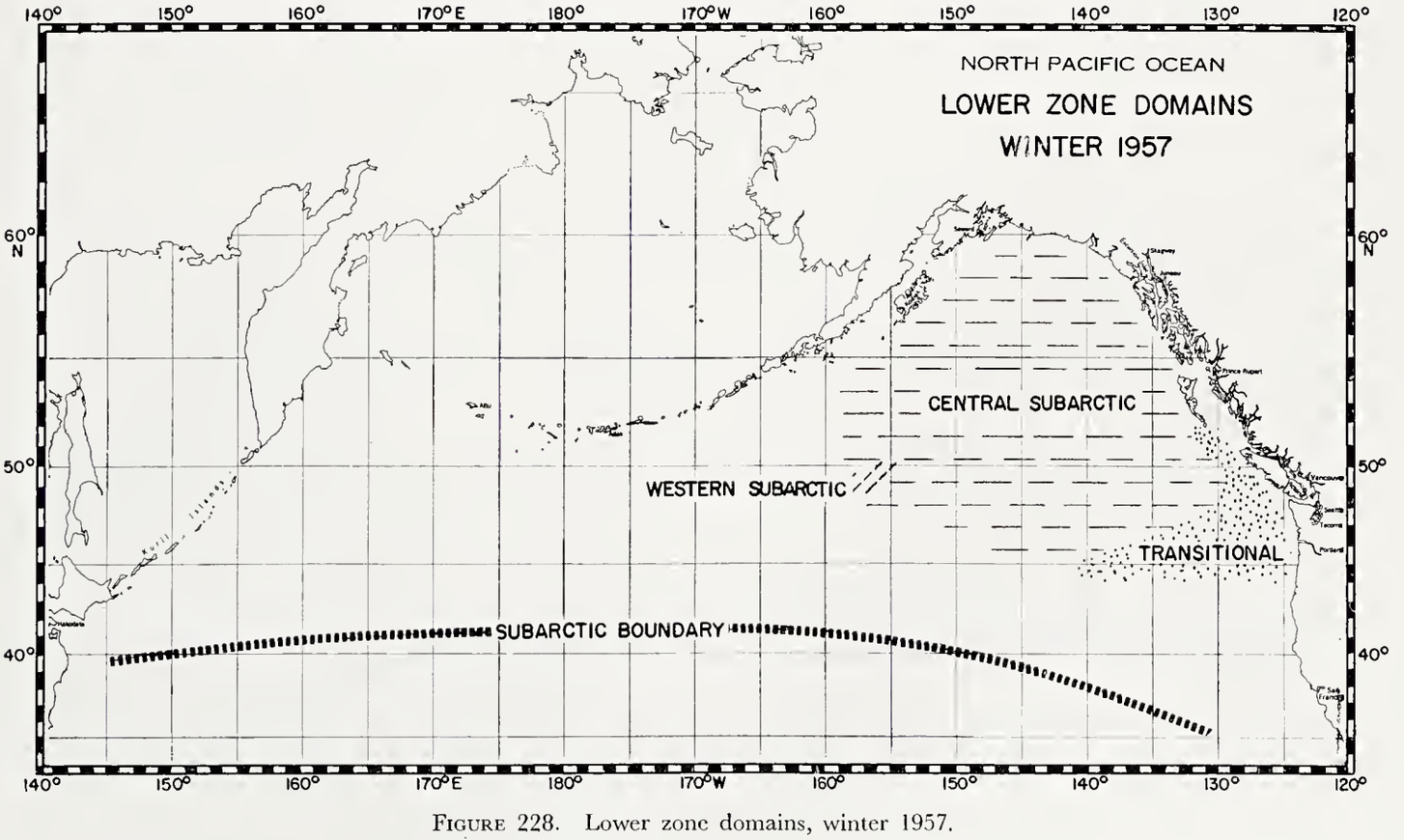


FIGURE 228. Lower zone domains, winter 1957.

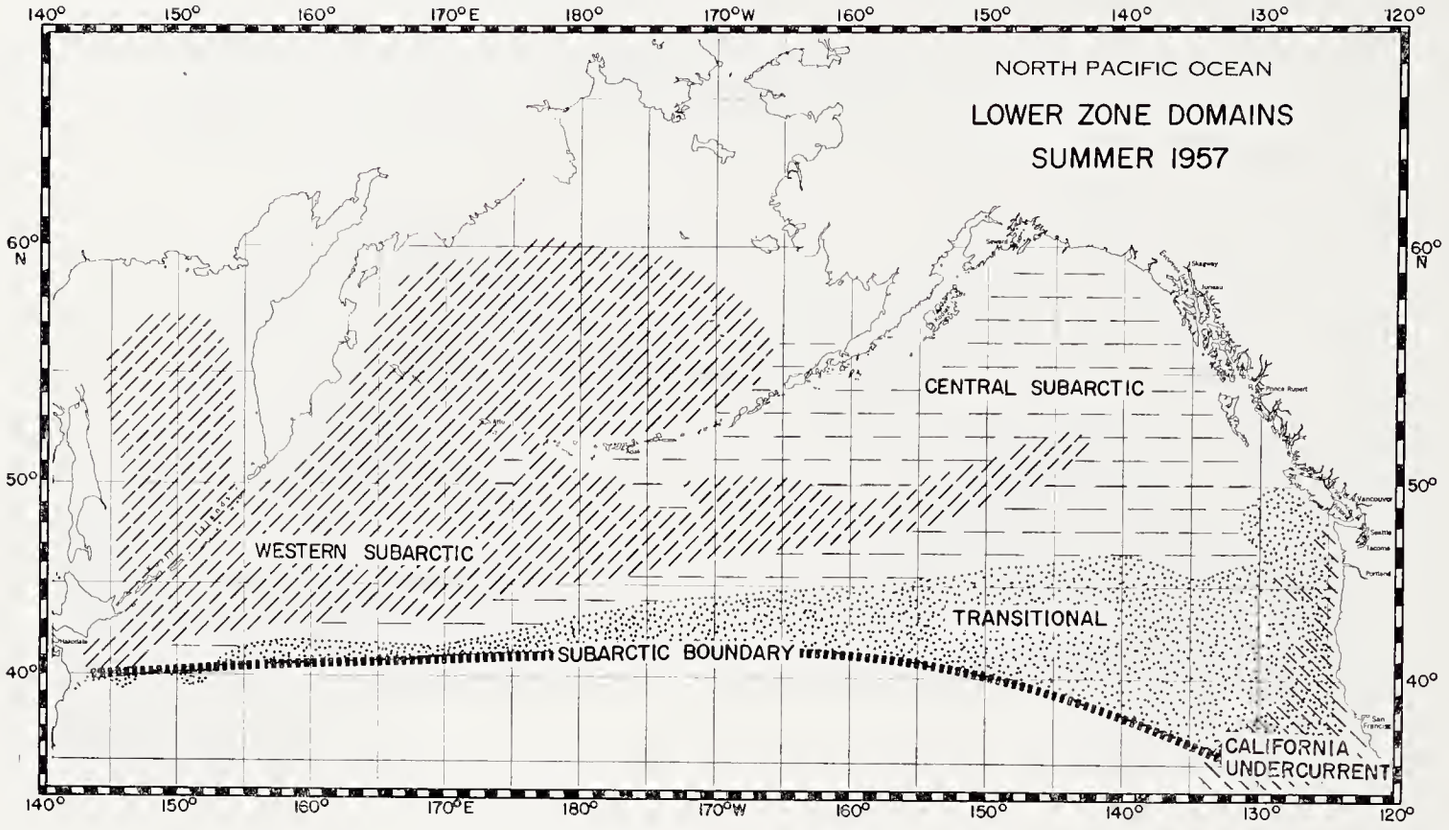


FIGURE 229. Lower zone domains, summer 1957.

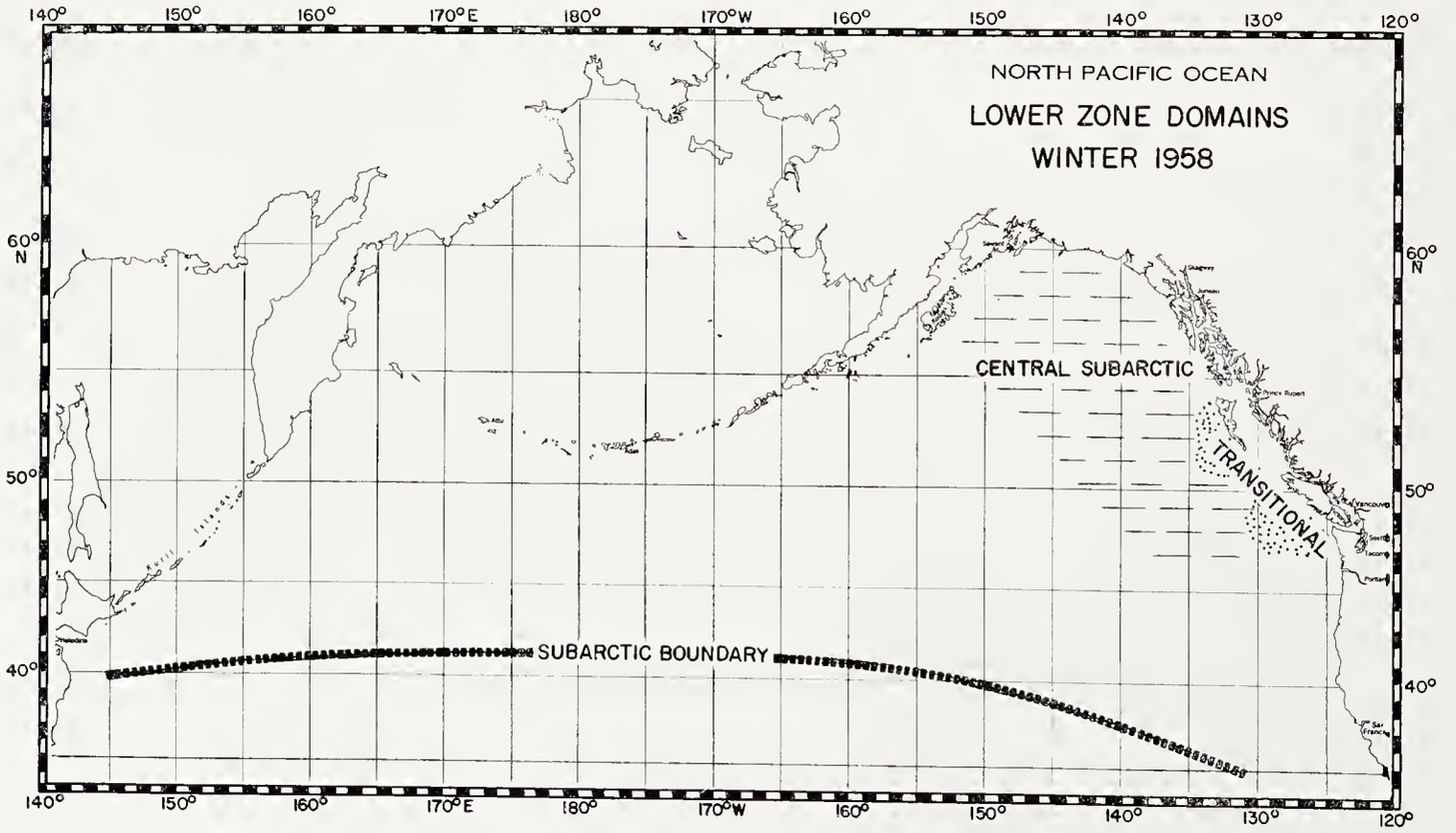


FIGURE 230. Lower zone domains, winter 1958.

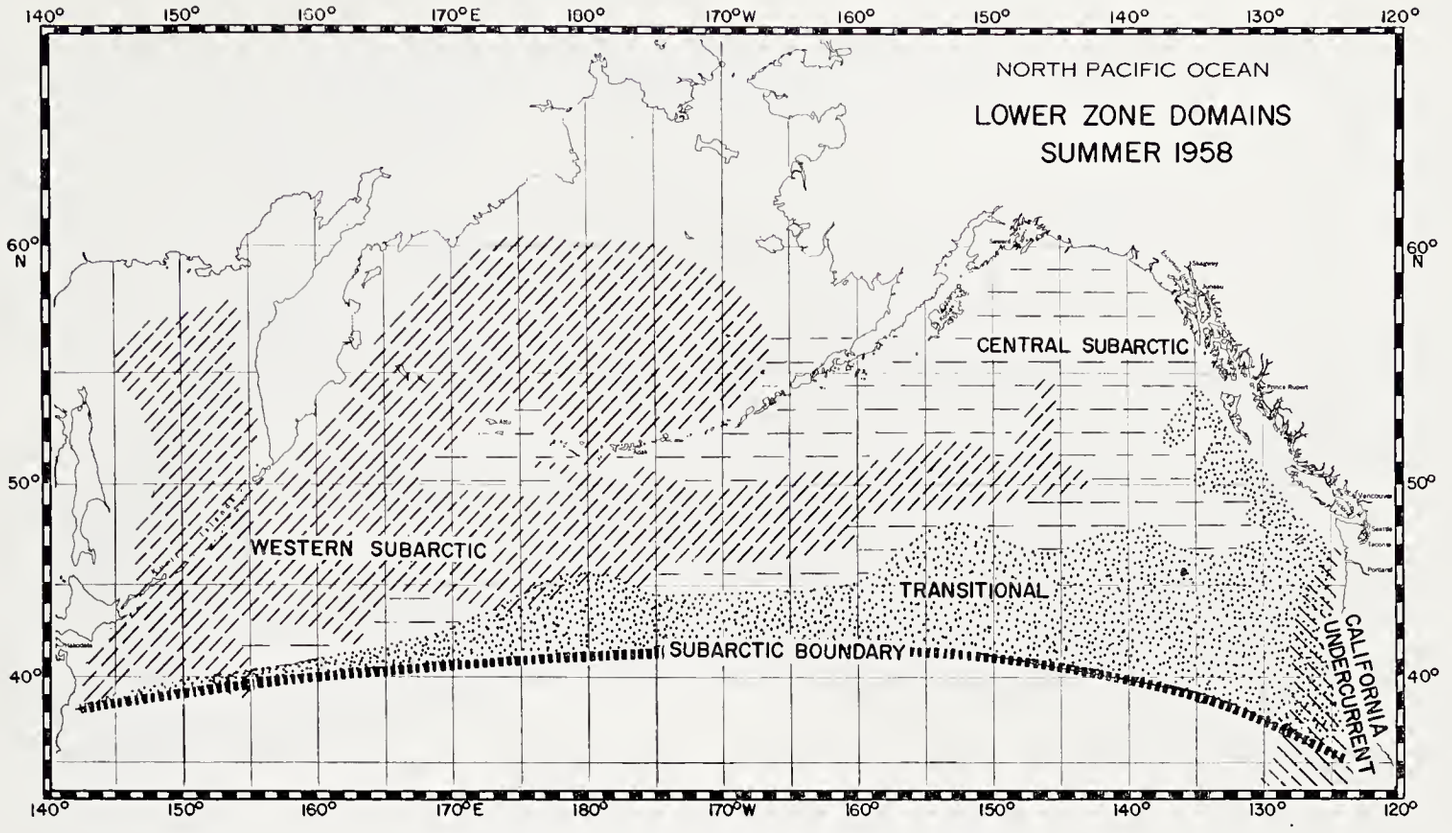


FIGURE 231. Lower zone domains, summer 1958.

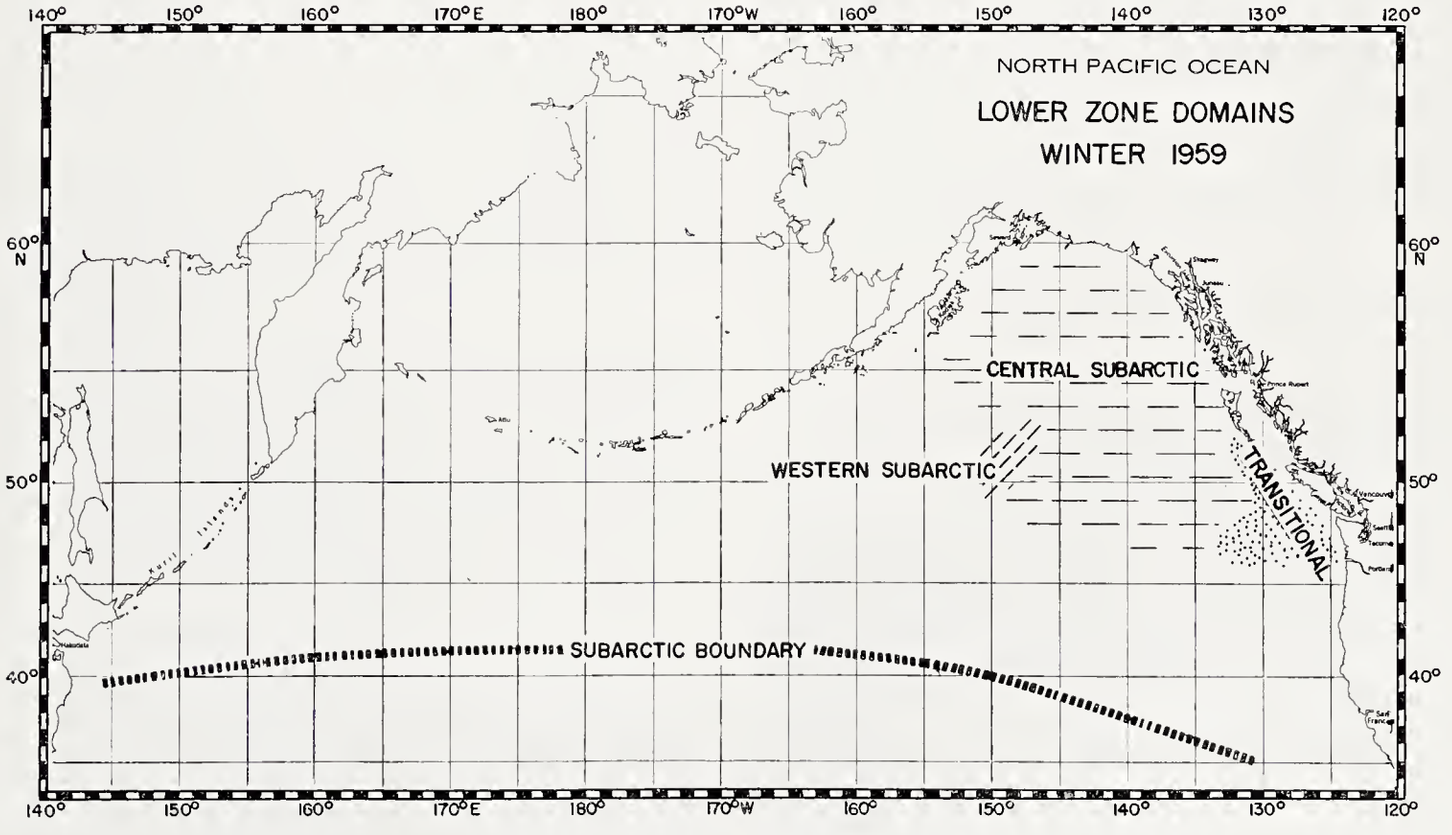


FIGURE 232. Lower zone domains, winter 1959.

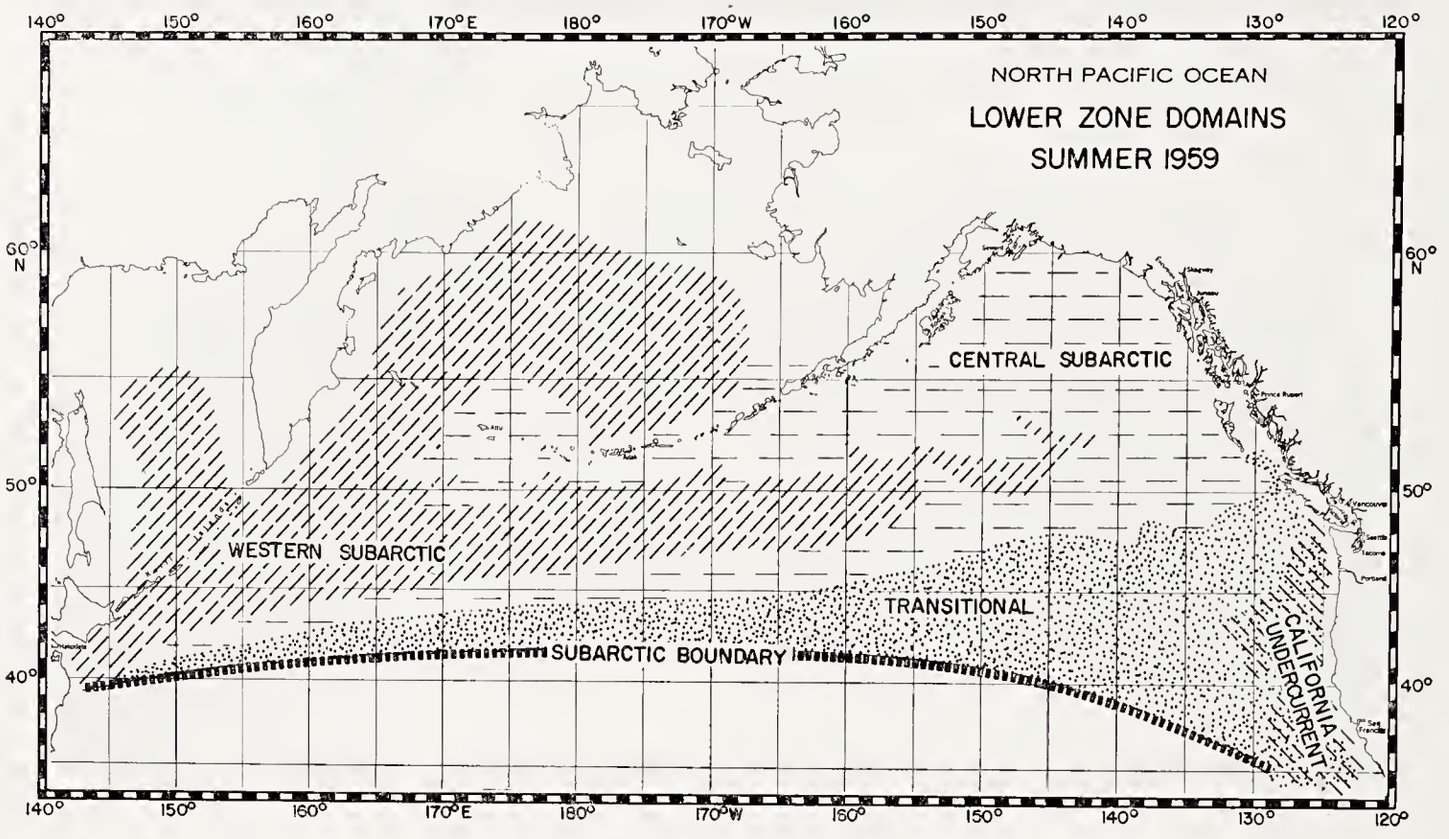


FIGURE 233. Lower zone domains, summer 1959.

APPENDIX I: OCEANOGRAPHY OF BRISTOL BAY

Description of Area

Bristol Bay is that part of the Bering Sea eastward of a line drawn from Cape Sarichef to the Kuskokwim River (App. I Fig. 1). It is the southeastern terminus of the shallow continental shelf in the Bering Sea, and is separated from the North Pacific Ocean by the Alaska Peninsula.

According to the U.S. Coast Pilot (1954) the annual mean air temperature is approximately 35°F. and the annual rainfall 30 to 40 inches; fog occurs during every month of the year. Depending on the severity of the winter temperatures, ice begins to form along the shore in October or November, grows until March and melts by April. Solid fields of drift ice have been reported offshore in the Bay as late as May.

Although the shores of the Bay are low, the encircling mountains form a large watershed area. In spring, after the ice breaks up in the rivers, snowmelt and runoff enter the Bay through numerous river systems such as the Kuskokwim, Nushagak, Kvichak, Naknek, Egegik, Ugashik and others. The extensive runoff during spring and summer and the presence of ice during winter result in a considerable range of oceanographic conditions in the shallow Bay.

The movement of water in the Bay is affected by runoff, ice, prevailing winds, tidal currents, and the movement of oceanic water off the continental shelf. Winds are usually from a northerly direction in late autumn and during winter, and shift to a southerly direction in late spring. The range of tide at the Naknek River entrance is about 24 feet and results in tidal currents in excess of three knots. This is contrasted with a tidal range of about three feet at the Pribilof Islands.

The Bay is of particular interest oceanographically because, as shown by recent drift bottle experiments, drifting objects enter the Bay from the extreme western Aleutians, the Gulf of Alaska, and as far south as lat. 45°N. in the central Subarctic (App. I Fig. 2). However, none have been recovered in the headwaters of the Bay.

Previous Oceanographic Investigations

The work of Saur *et al.* (1952) discussed earlier (p. 7) included a summary of cruises conducted in the Bering Sea. Omitted from this summary were cruises by the Japanese Fisheries Training School vessel *Hakuho Maru* during 1930 and 1933 to 1936, and the U.S.C.G.T. *Redwing* during 1938 to 1941.

Since 1956 oceanographic data have been obtained in Bristol Bay from vessels chartered by the U.S. Bureau of Commercial Fisheries in conjunction with crab investigations. Most of these data are not published.

Hebard (1959) obtained direct-current measurements at four locations in the Bay during June 1957 and ascertained the presence of rotary (although elongated in northeast and southwest direction) tidal currents. Velocities of 0.1 to 1.7 knots were observed with little difference between the direction of flow at the surface and the bottom. A net or average flow of less than 0.1 knot in a counterclockwise direction was deduced.

An oceanographic survey in the Bering Sea during winter 1955 (U. S. Navy Hydrographic Office, 1958) greatly contributed to an understanding of oceanographic conditions on the continental shelf. It was known that during the winter most of the shelf area is covered with sea ice, and one was temped to speculate that the freezing-out process would result in the formation of cold, very saline water. This would result in very dense, bottom water that would flow off the continental shelf seeking a lower level of equivalent density. The 1955 data showed that in the Bristol Bay area the water column was isothermal with temperatures of −0.5°C. to −1.5°C. (App. I Fig. 3) and isohaline with salinities of 31.5‰ to 31.8‰ (App. I Fig. 4). Similar temperatures and salinities have been found on the shelf at depths from 50 to 100 metres during spring and early summer. Hence, this water is not dense enough to form intermediate or bottom water in the Bering Sea.

Oceanographic Investigations, U.S.C.G.T. *Redwing*

These surveys during 1938 to 1941 are by far the most extensive and complete ever obtained in Bristol Bay. The work was terminated by World War II and since there is no record of prior analysis of these data, they are used to a great extent in this report to define conditions in the Bay. This is justified by the fact that conditions (temperature and salinity) have not appreciably changed from that period to the present day. Recent oceanographic coverage is not adequate to show a comparison of specific properties at specific depths; however, comparison of average monthly air temperatures for 1939 and 1959 at Dillingham (located near the head of the Bay) (shown in App. I Fig. 5) provides convincing evidence that

the climate has been relatively stable.

The *Redwing* investigations were based upon a network of oceanographic stations at 20-mile intervals that extended from the headwaters of the Bay out over the continental shelf. Stations were repcated during the same and subsequent years.

During 1938, stations were occupied during August and September. The vertical distributions of salinity and density (sigma-t) presented by Favorite and Pedersen (1959 a) show two of the most characteristic features of the Bay—the counterclockwise flow as shown by the density profile between Cape Seniavin and Cape Newenham (App. I Fig. 6); and the vertical homogeneity of the water column at the head of the Bay as shown by the salinity profile seaward of Cape Chichagof (App. I Fig. 7).

Another interesting feature revealed by the 1938 data was the thermal stratification of the water column. Values of temperature, salinity and current speed at station 30–6 are shown in Appendix I Table 1. Between 15 and 16 metres depth the temperature decreased 4.76°C. In this particular case, the water column was essentially isohaline. Current speeds show no appreciable change in the area of the temperature discontinuity indicating that solar heating is the dominant cause of the temperature structure.

Appendix I Table 1.

Station 30–6 Z	57°00′N.; 160°37′W. Temperature	August 15, 1938 Salinity	Speed
0	(10.76)	(31.85)	*
5	(10.66)	(31.85)	*
10	(10.44)	(31.85)	*
12	*	*	.59
15	10.39	31.85	.49
16	5.63	31.85	.40
17	5.13	31.87	.48
18	4.97	31.85	.44
19	5.00	31.87	.42
20	4.97	31.87	.47

( ) Observation recorded two hours earlier—vessel anchored.
* No observation made.

Extensive hydrographic and current data were collected during May to August, 1939 (Favorite *et al.*, 1961). Surface current measurements, obtained by observing the set and drift of a drift-stick released from the anchored vessel at various locations provided a fairly comprehensive picture of tidal currents (App. I Fig. 8). The water in the Bay oscillated in a northeast-southwest direction. Velocities in excess of two knots occurred along the shore and considerably reduced velocities were found in the central part of the entrance of the Bay. Thus, even though the survey was as synoptic as possible utilizing one vessel (approximately 2-hour time interval between stations), the structure probably varied rapidly and considerably. Nevertheless, stations occupied as many as three times during the period May to August permit a gross picture of conditions in the Bay during the spring and summer.

Temperature Distribution, 1939

Three locations that exhibit representative temperature structurcs have been selectcd from the 1939 data (App. I Fig. 9). The observations were obtained in June, July, and August.

At the entrance to the Bay (Station A) the June temperature structure was isothermal at approximately 1°C. We can assume from Appendix I Figure 3 that during winter the temperature was about −1.5°C. Thus, by June, heat from solar incident radiation had been distributed uniformly throughout the water column and increased the temperature of the water column by about 2.5°C. We can also assume that some of the radiation had been utilized to melt the supposed ice cover. During June and July, most of the heat gain was confined to the upper 10 metres, resulting in a sharp 6°C. thermocline. As implied in Appendix I Figure 4, and as will be shown in the next section, the water column was essentially isohalinc; thus, the water column may be considered thermally stratified and the 1.5°C. temperature increase in the lower layer was the result of diffusion, and advection. By August, surface cooling and mixing had already begun as evidenced by the deepening of the thermocline. However, as shown subsequently in the discussion of surface temperatures, another process was involved in cooling the surface waters in the central part of the Bay, and maximum surface temperatures of about 10°C. can be expected in late summer.

At Station B in June the waters near the surface were warmer than at A and were in the 5°C. range. This increase in heat content is believed to be due to the shallow dcpth, which presented a smaller water column to be heated, as well as the fact that part of this water column was fed by the river runoff which gained additional heat while passing over the warm and very shallow flats at the head of the Bay. During July and August there was a progressive increase in the water temperatures to 10°C., and tidal and wind mixing usually resulted in isothermal conditions.

Conditions at Station C were similar to those at Station B; but, because the depths were considerably shallower, the waters were correspondingly warmer. By August, temperatures in the 12°C. range were evident. Thus, in winter, the offshore conditions are

isothermal at about −1.5°C. and during spring and summer a pronounced shallow thermocline develops. It begins to decay in late summer or early autumn. Whereas inshore, where similar winter conditions can be assumed to prevail, a minor thermocline develops in spring, but quickly disappears in summer.

Horizontal temperature distribution indicates that there was a sharp separation between the inshore and offshore areas. Surface temperatures during May and June (App. I Fig. 10) showed a marked temperature front lying along a line from Port Heiden to Cape Peirce; seaward of the front, temperatures in the 1°C. and 2°C. range were found, and a counterclockwise flow was indicated. However, shoreward of the front the isotherms showed the presence of another more pronounced counterclockwise eddy or gyre. It appears that the warm dilute runoff has been contained eastward of the Cape and been forced to recirculate shoreward of the front. The absence of an indication of this inshore gyre in the bottom temperature distribution (App. I Fig. 11) implies that this feature is confined to the surface. The time interval and area involved indicate that this is not a tidal phenomenon.

By August, the generally accepted peripheral counterclockwise flow in the Bay is evident from the surface isotherms (App. I Fig. 12). However, just inshore of the temperature front which extended across the Bay in spring, an anomalous region of cold temperatures occurred which is interpreted as an area of upwelling. Again, as in spring, the bottom temperature distribution (App. I Fig. 13) shows an almost uniform gradient of temperatures from the head of the Bay seaward. The area of cold temperatures at the surface, indicative of upwelling, and a similar gradient of bottom temperatures were also present in August 1938.

Appendix I Figure 14 which shows the difference between surface and bottom temperatures during August 1939 clearly indicates the absence of any thermocline in the water column inshore of a line between Port Heiden and Cape Peirce. One would also expect to see a considerable difference in the turbidity and water colour on either side of this boundary, but no data are available.

Salinity Distribution, 1939

The salinity distribution in the Bay corresponded to the temperature distribution. As shown in Appendix I Figure 4, the 1955 winter conditions show the water structure to be isohaline with the central shelf area having a salinity of about 31.8‰. Appendix I Figure 15 shows the vertical distribution of salinity during June, July, and August 1939 at the same stations (A, B, and C) discussed in the temperature section.

At location A the water column was isohaline at about 31.8‰ during all three months. At B, which was further inshore, isohaline conditions also prevailed. Dilution occurred in July, but in August more saline conditions were encountered. This is due to an intrusion from the southwest which is evident in the horizontal distributions that follow. An adjacent station reflected the progressive dilution characteristic of the inshore area, which was clearly reflected in the values at C during August. By late August, the temperatures reached a maximum and began to decrease, however, there is evidence that further dilution occurred after this period. The absence of an appreciable halocline offshore at Position A implies that the river runoff moved counterclockwise along the coastline and did not extend to the central part of the Bay.

Surface salinities during May–June, 1939 (App. I Fig. 16) also indicate an inshore counterclockwise gyre which moved coastal dilution southward, inshore of the temperature front previously discussed. The differences in salinity values between the surface and bottom (App. I Fig. 17) show the feature to be confined to the surface waters at the head of the Bay. By August (App. I Fig. 18) the tongue of dilute water had been transported northwestward out of the Bay. The low salinity values at the head of the Bay indicate that there still was an extensive extrusion of runoff into the Bay in late summer. Salinity distribution at the bottom is shown in Appendix I Figure 19.

Approaches to Bristol Bay

In 1940 part of the emphasis of the *Redwing* investigations was shifted seaward of the Bay and this permits showing a possible source of the upwelled water.

The surface temperatures in August (App. I Fig. 20) varied from 5°C. to 11°C. The low temperatures which are shown near the Pribilof Islands are attributed to turbulence and a downward transfer of heat rather than any unusual source of cold water from the oceanic areas. The warmest water is found, as would be anticipated, along the shores of Bristol Bay. The cold area in the central part of the mouth of the Bay between Port Heiden and Cape Peiree is also evident.

Bottom temperature contours (App. I Fig. 21) coincide with the bottom topography. The cold area eastward of the Pribilof Islands is believed to reflect the delay in melting of offshore ice, and thus a delay of seasonal warming of the water column.

The bottom salinities (App. I Fig. 22) show a shoreward intrusion of oceanic water, between the Pribilof Islands and Unimak Island, which was confined seaward of a line between Port Heiden and Cape Peirce. The salinity distribution dominates the distribution of density as shown by the contours of sigma-t (App. I Fig. 23). However, it is impossible to ascertain from the data if the movement of water at these depths is along the isolines. If so, the oceanic water moves counterclockwise around the Bay. If it flows across the isolines the water intrudes into the Bay as a tongue or wedge resulting in an upward movement or upwelling.

Edge of Continental Shelf

A discussion of Bristol Bay would not be complete without showing the distribution of properties in the zone between the continental shelf and the oceanic area seaward of the shelf. In this case, the most complete data are from the cruise of the M/V *Attu* (Favorite and Pedersen, 1959 b).

Vertical profiles of temperature, salinity, dissolved oxygen and density are shown in Appendix I Figure 24.

The line of stations did not extend far enough onto the shelf to show the cold temperatures, characteristic of this area, as shown in Appendix I Figure 21. Surface warming had already begun; hence, there was very little indication of the changes in temperature conditions as one approaches the shelf from seaward that are evident in the salinity profile structure. Values of dissolved oxygen greater than 0.7 mg. at./l. near, and over the shelf, indicate high phytoplankton population.

Although solar heating in spring and summer tends to make the surface temperatures relatively uniform over and seaward of the shelf, the presence of ice, or the temperatures that exist immediately after the ice has melted, reveal a marked change in environment at the edge of the continental shelf. Data collected aboard the M/V *Tordenskjold* (Love, 1959) during 1956 illustrated this condition (App. I Fig. 25).

Summary

Bristol Bay is characterized by an extensive shallow continental shelf which isolates the Bay from the oceanic circulation systems, and by an extensive watershed surrounding the Bay which releases large amounts of snowmelt and fresh-water runoff into the Bay from early spring to late autumn. The combination of these features and the wind and tidal systems result in a relatively constant annual cycle of environmental conditions, which are in sharp contrast to those of the adjacent Bering Sea. The boundary between the shelf area and the deep Bering Sea basin, delineated by the sharp continental slope, is also evidenced by changes in physical and chemical properties of the water column.

In early autumn, the heat content of the shallow Bay is quickly dissipated. Cold air temperatures and dilute surface water permit the early formation of ice along the shores, and by winter, ice is present over a large part if not all of the Bay. During winter, temperatures and salinities of approximately −1°C. and 31.6‰ occur in the ice fields; whereas, in contrast, the central Bering Sea is usually void of ice and temperatures from 2°C. to 3°C. and salinities of 33.0‰ to 33.4‰ occur at the surface.

The ice cover in the Bay retards the spring warming of the surface layer, but melting of the ice dilutes the surface layer causing sufficient vertical stratification to confine the rapidly increasing net heat gain to the upper 10 to 20 metres of the water column. In the inshore area the temperatures reach 12°C. to 13°C. and the water column is isothermal. In the offshore area, summer heating results in the formation of a shallow, sharp thermocline with a magnitude of 5°C. to 8°C. in mid-summer. Surface temperatures reach 10°C. to 11°C. In late summer, wind mixing, advection and vertical diffusion can raise the bottom temperatures in the offshore waters to temperatures of 3°C. to 4°C. or higher.

The movement of water in the Bay, as implied by the distribution of properties, is counterclockwise. Drift stick and direct current measurements indicate the water in the Bay oscillates with a tidal period from the surface to the bottom in a northeast-southwest movement; however, slope currents induced by the wind, and pressure distributions in the Bering Sea must also produce short and long term effects on the general flow which were not obvious in these current measurements.

One of the striking oceanographic features of the Bay is the evidence of a sharp boundary between the headwaters and the offshore waters. This occurs in the central part of the Bay along a line between Cape Peirce and Port Heiden and appears to be associated with a vertical movement of water intruding over the continental shelf between the Pribilof Islands and Unimak Island.

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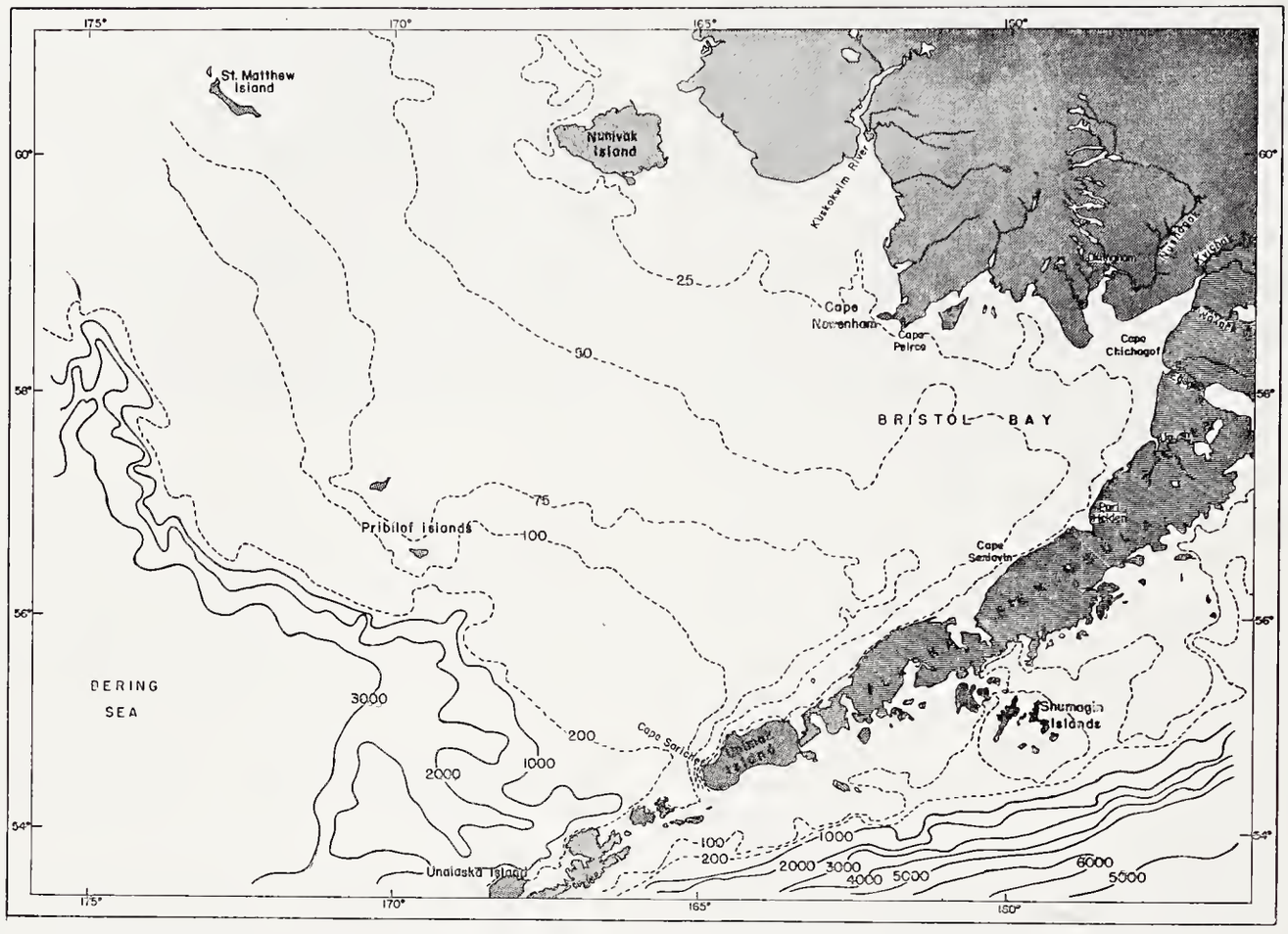
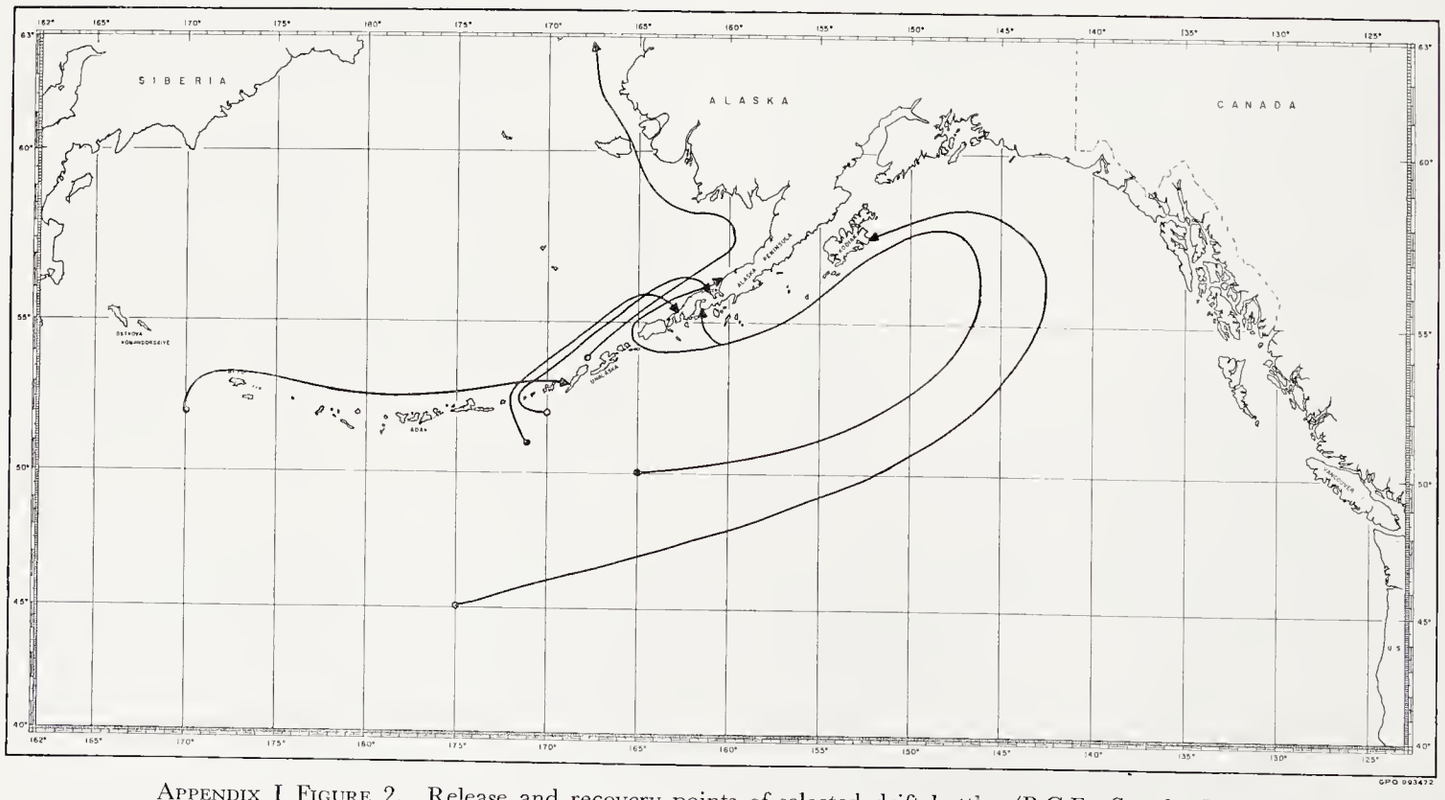
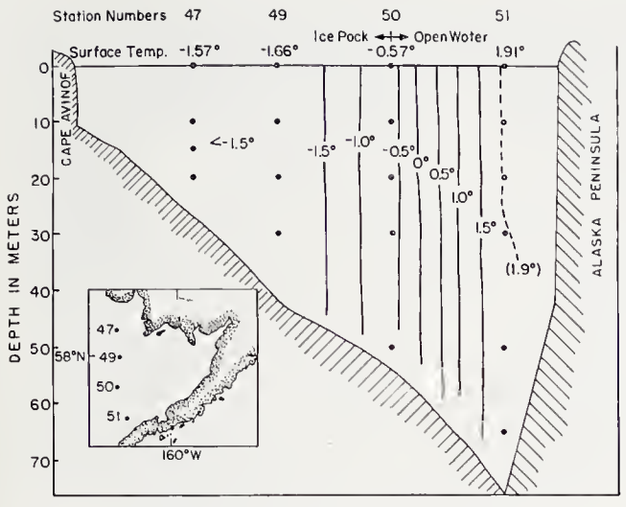


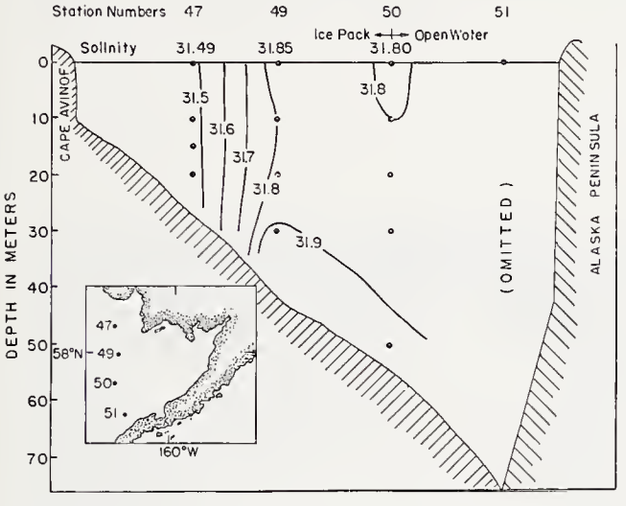
Appendix I Figure 1. General area chart showing selected contours of bottom topography in metres. (25, 50, and 75 metre contours not shown southward of Alaska Peninsula.)



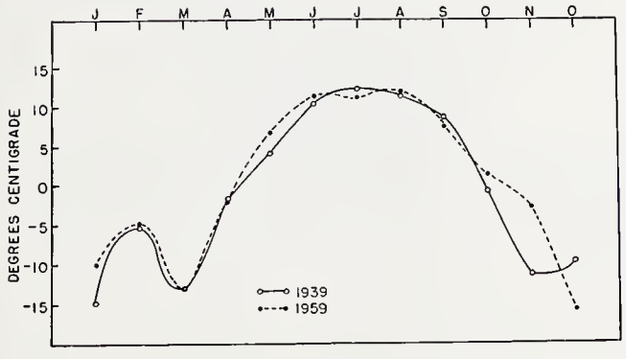
Appendix I Figure 2. Release and recovery points of selected drift bottles (B.C.F., Seattle, Wash.).



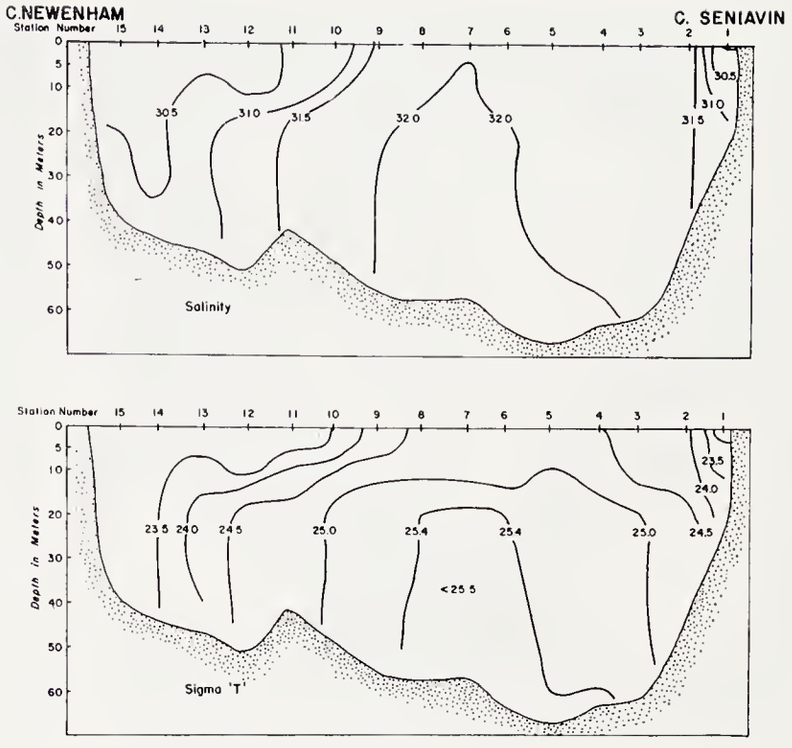
APPENDIX I FIGURE 3. Vertical profile of temperature (°C.) at entrance to Bristol Bay, winter 1955.



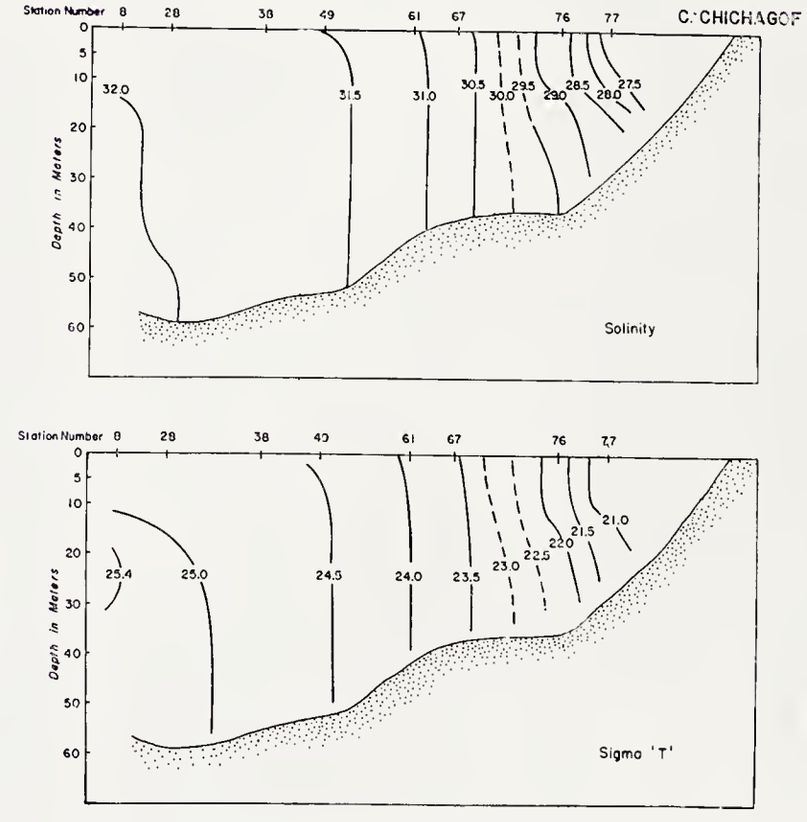
APPENDIX I FIGURE 4. Vertical profile of salinity (‰) at entrance to Bristol Bay, winter 1955.



APPENDIX I FIGURE 5. Comparison of average monthly air temperatures during 1939 and 1959 at Dillingham, Alaska.

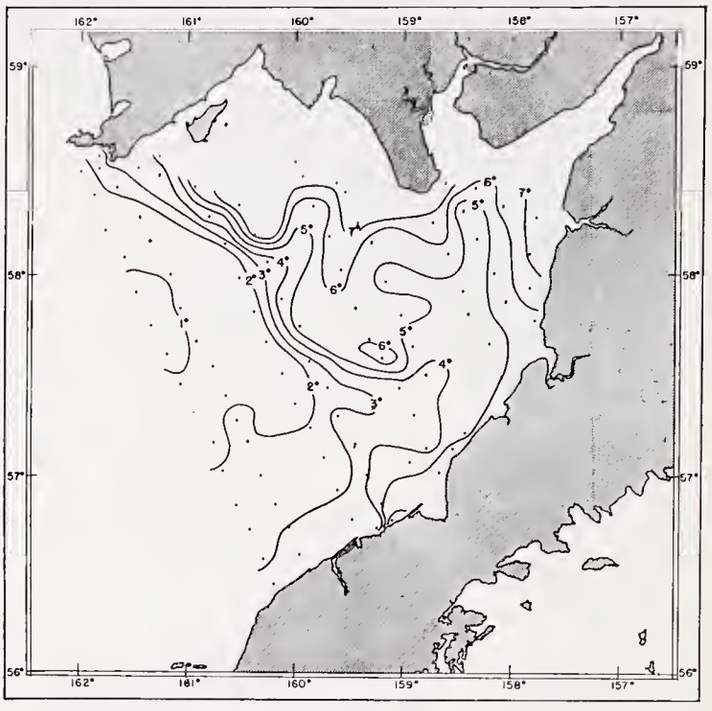


APPENDIX I FIGURE 6. Vertical profiles of salinity and sigma-t between Cape Seniavin and Cape Newenham, August 1938.

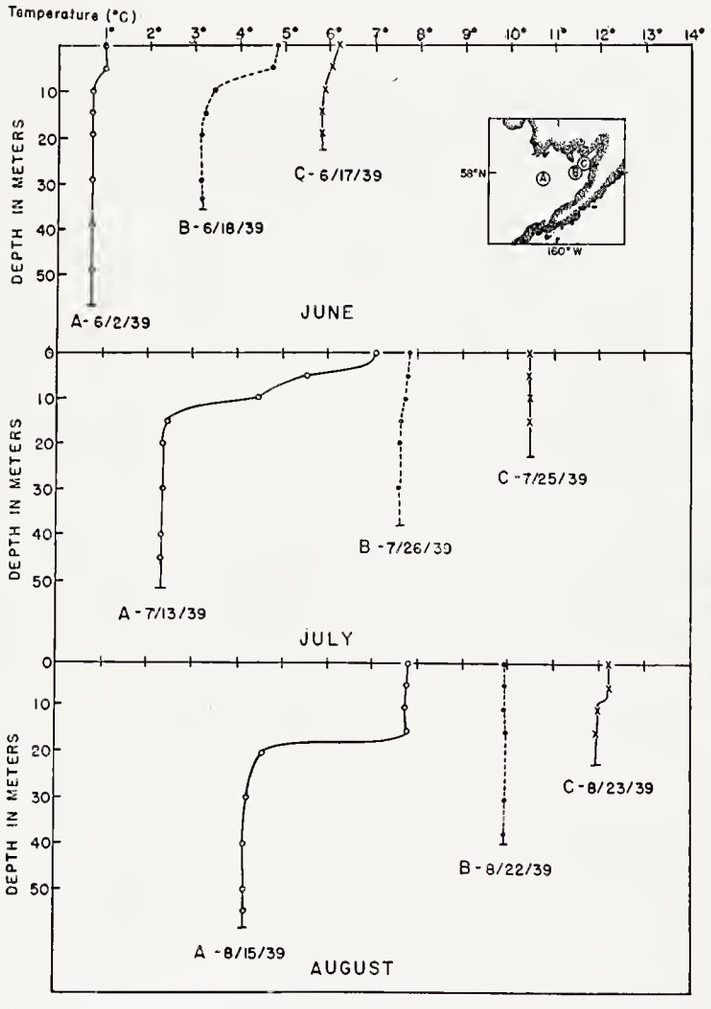


APPENDIX I FIGURE 7. Vertical profile of salinity and sigma-t seaward of Cape Chichagof.

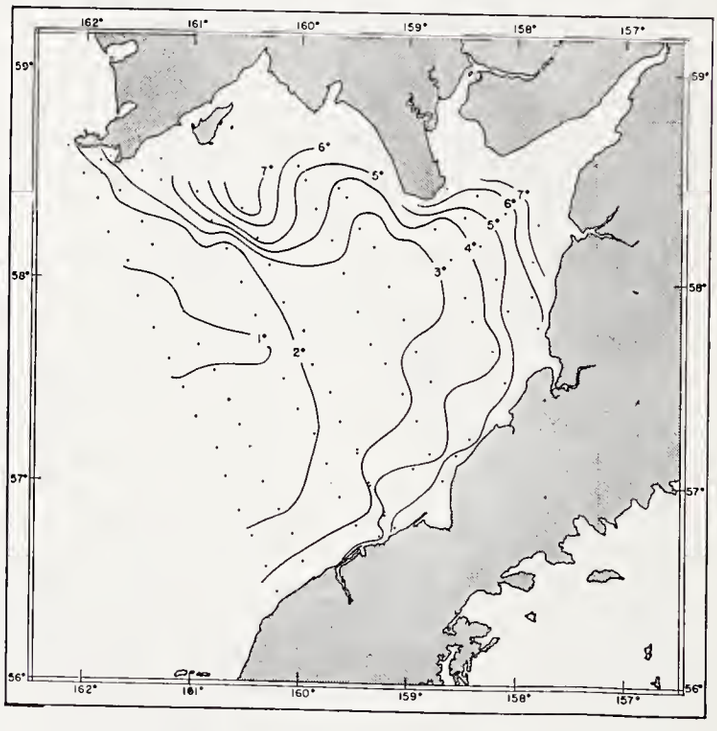
APPENDIX I FIGURE 8. Surfaee drift-stick observations, 1939.



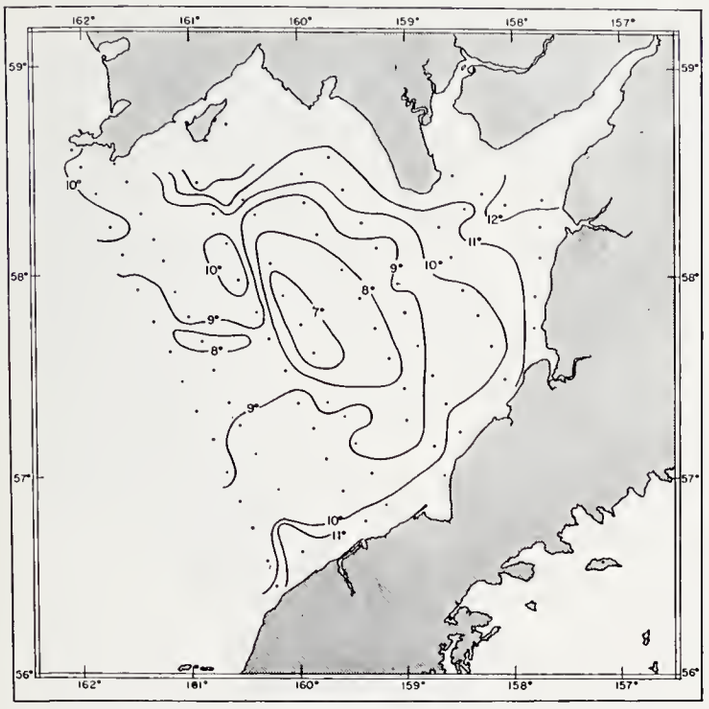
APPENDIX I FIGURE 10. Surface temperatures (°C.), May–June 1939.



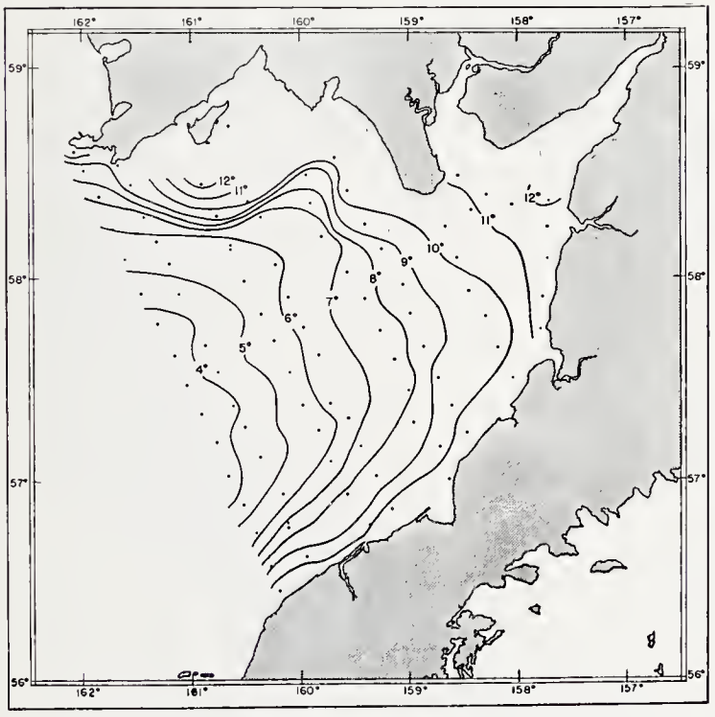
APPENDIX I FIGURE 9. Vertical temperature structure at three selected stations, 1939.



APPENDIX I FIGURE 11. Bottom temperatures (°C.), May–June 1939.

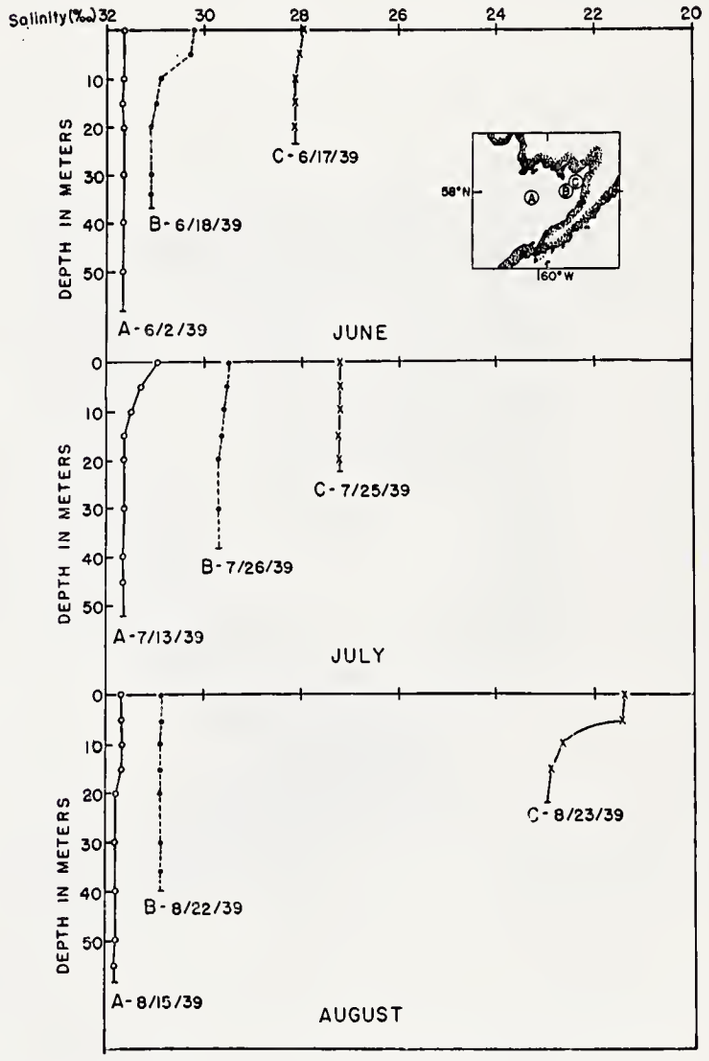


Appendix I Figure 12. Surface temperatures (°C.), August 1939.

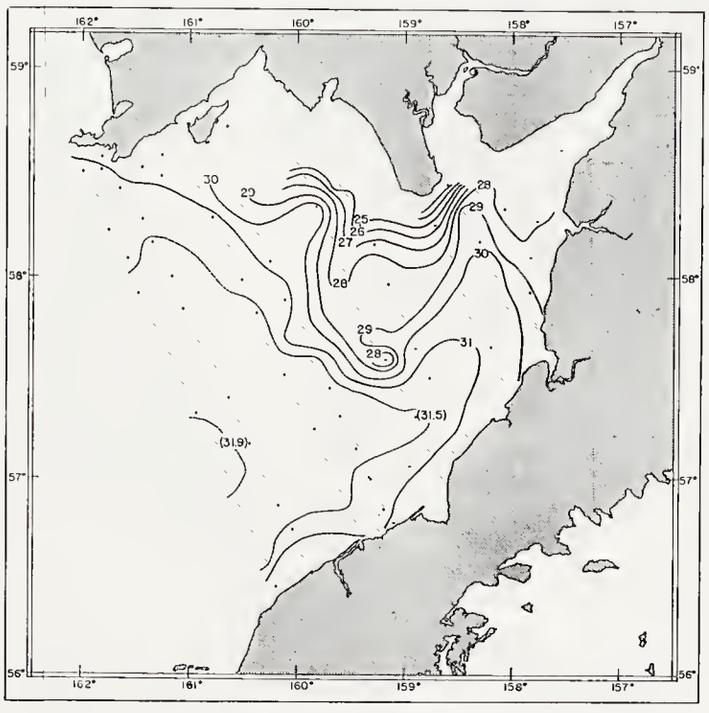


Appendix I Figure 13. Bottom temperatures (°C.), August 1939.

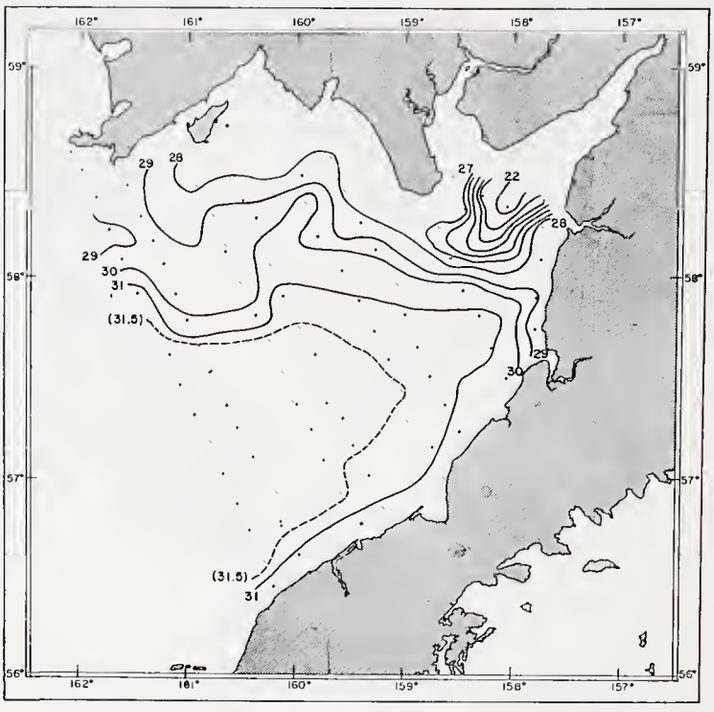
Appendix I Figure 14. Difference in temperature (°C.) between surface and bottom, August 1939.



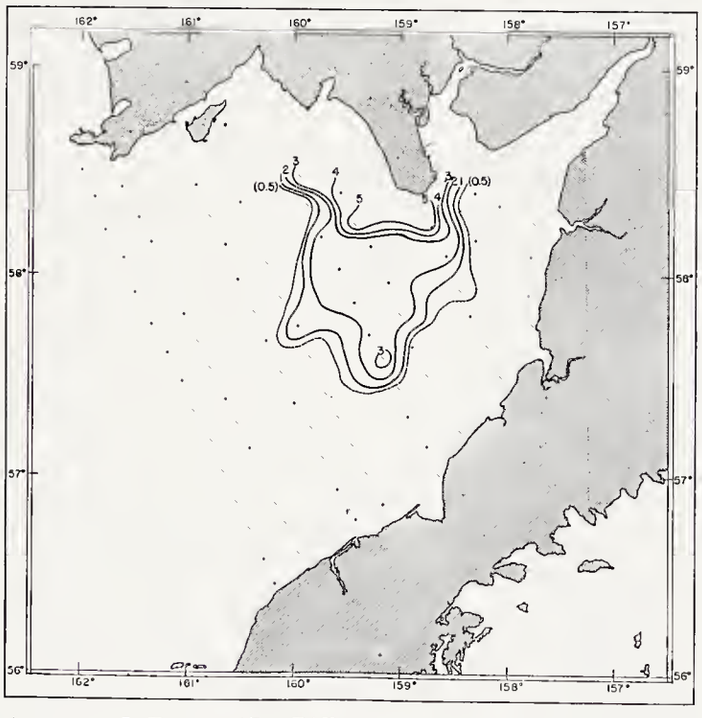
Appendix I Figure 15. Vertical salinity structure at three selected stations, 1939.



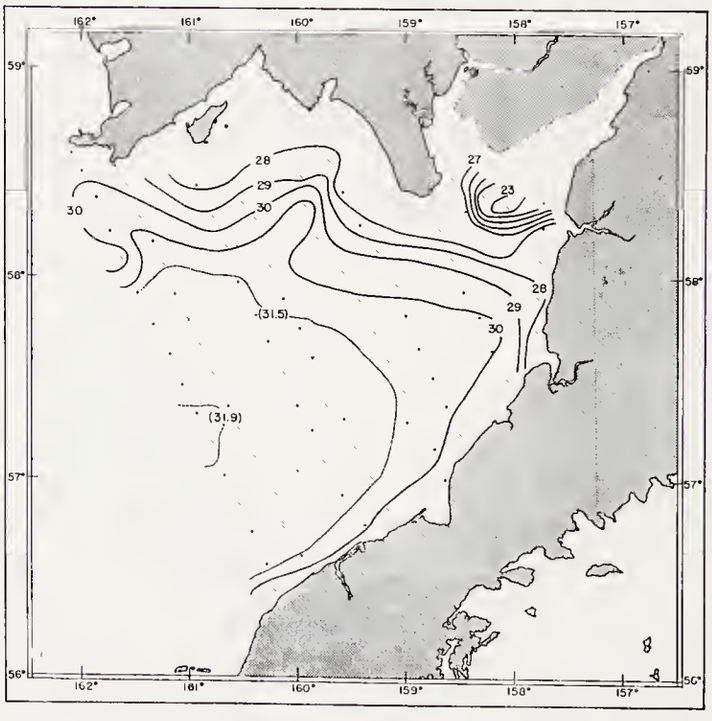
Anppnedix I Figure 16. Surface salinity (‰), May–June 1939.



Appendix I Figure 18. Surface salinity (‰), August 1939.



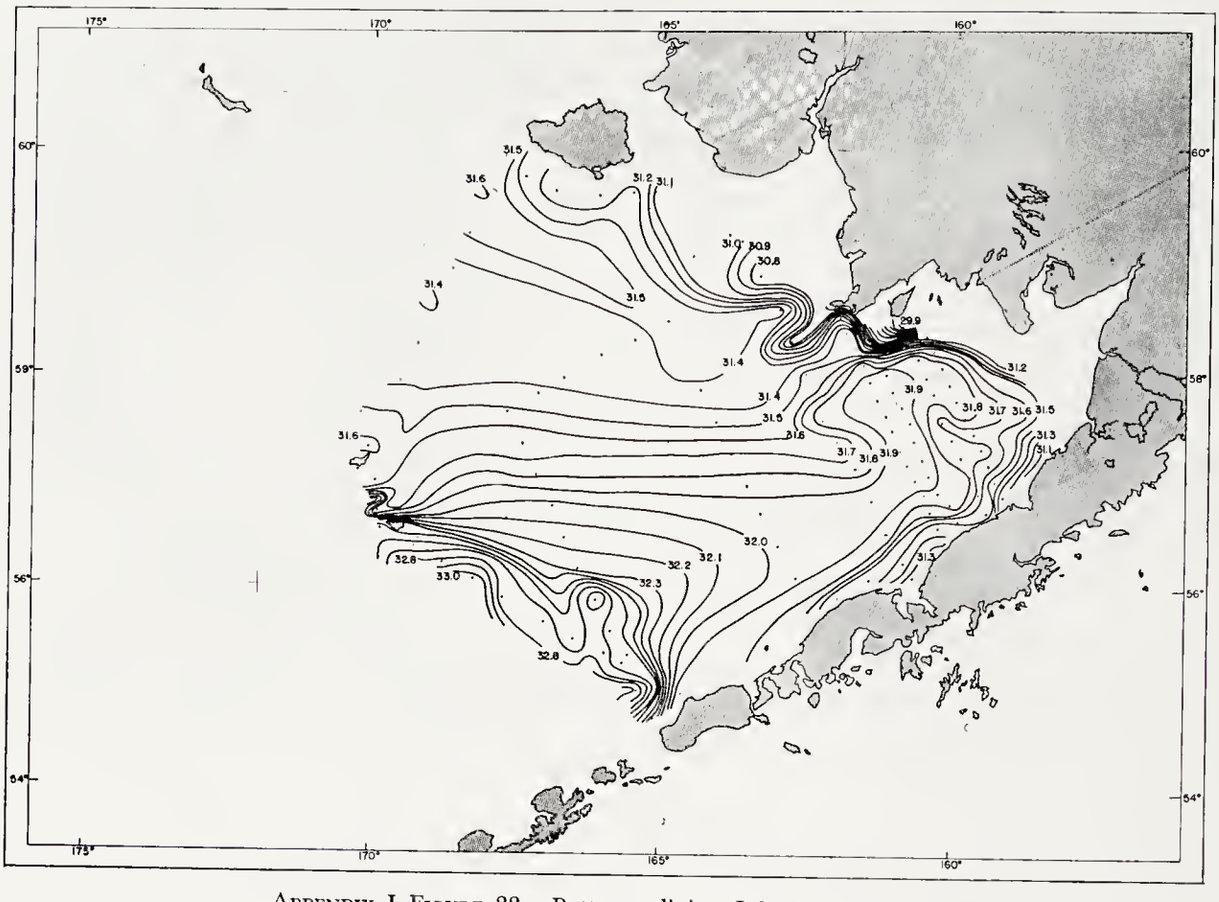
Appendix I Figure 17. Difference in salinity (‰) between surface and bottom, May–June 1939.



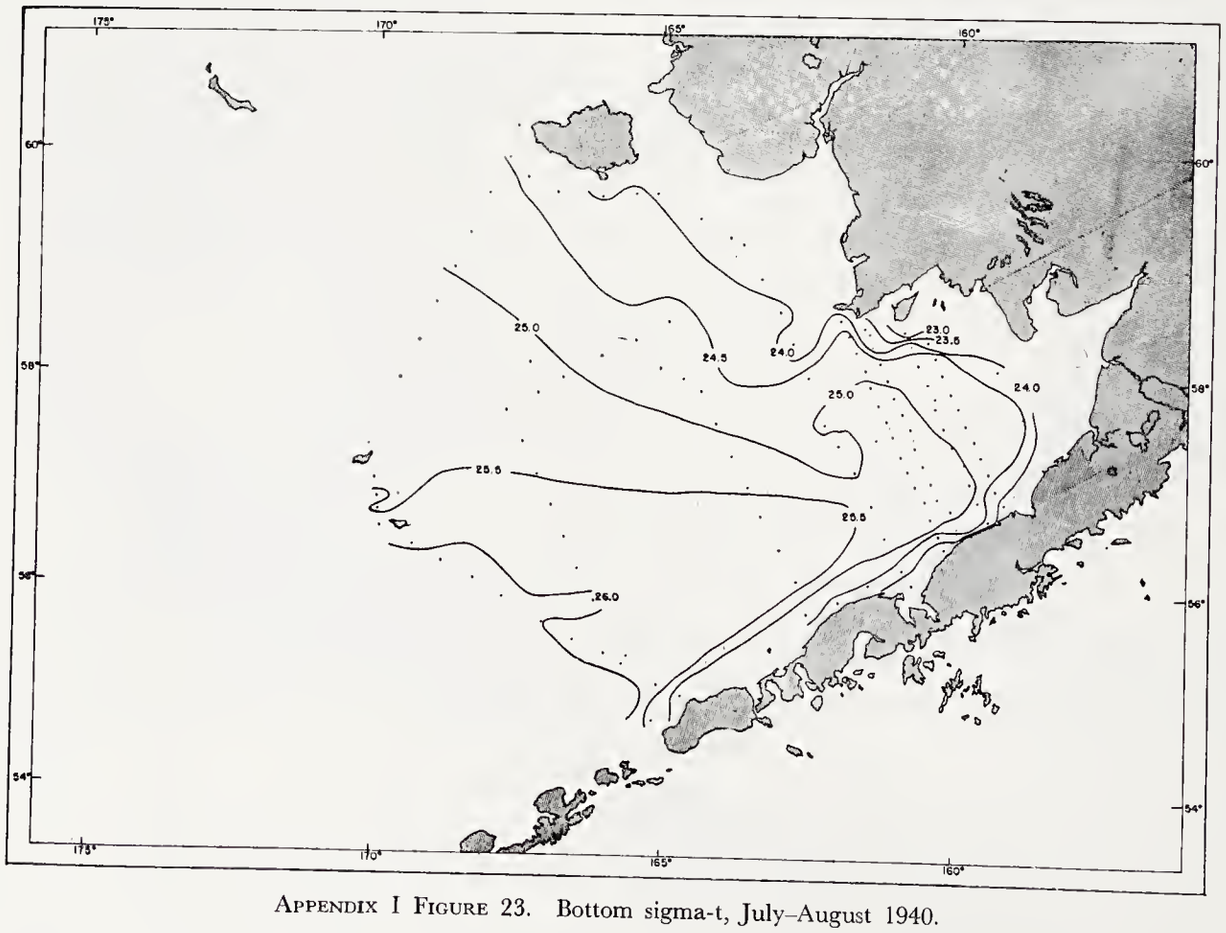
Appendix I Figure 19. Bottom salinity (‰), August 1939.

Appendix I Figure 20. Surface temperatures, July–August 1940.

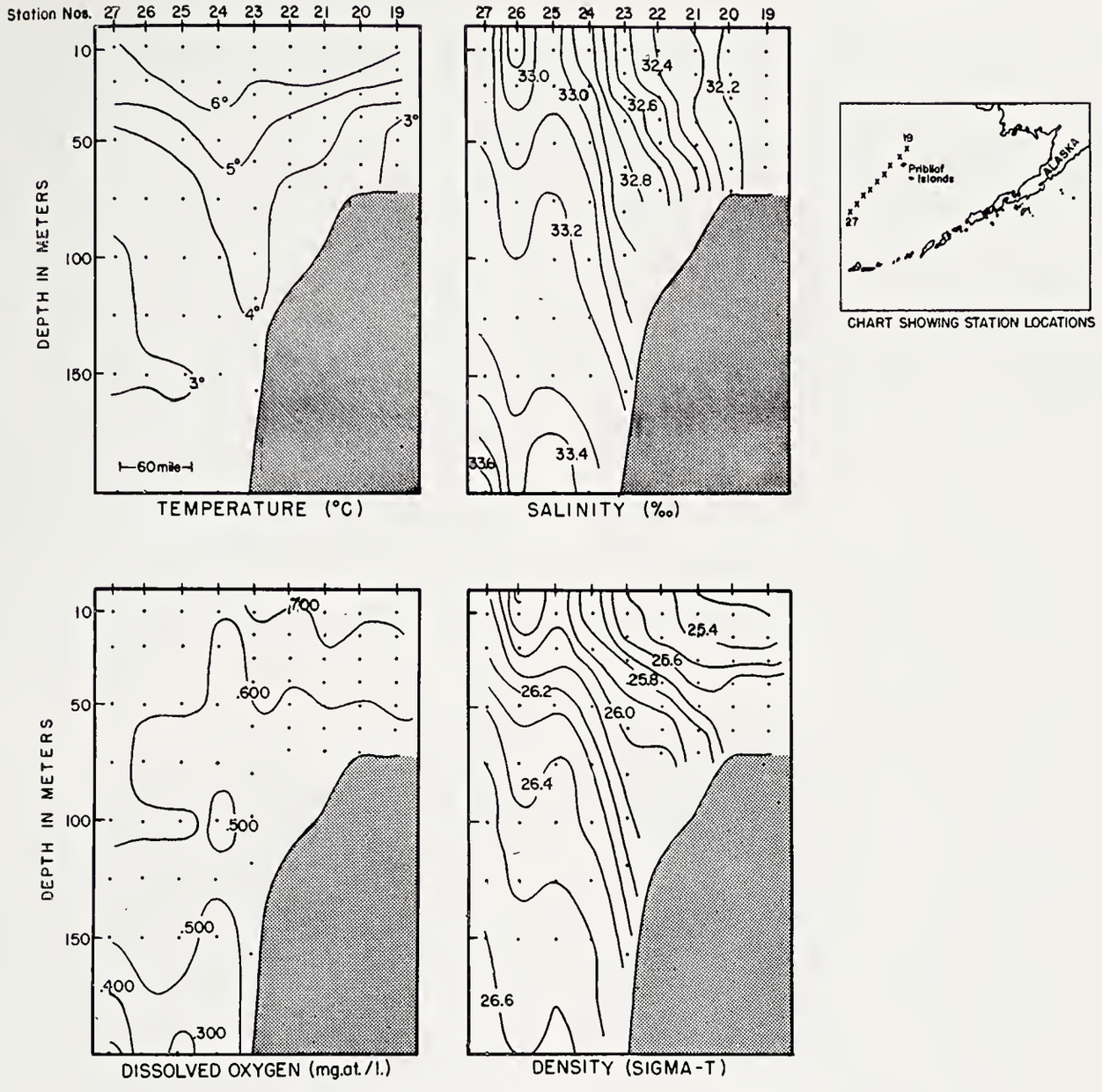
Appendix I Figure 21. Bottom temperatures, July–August 1940.



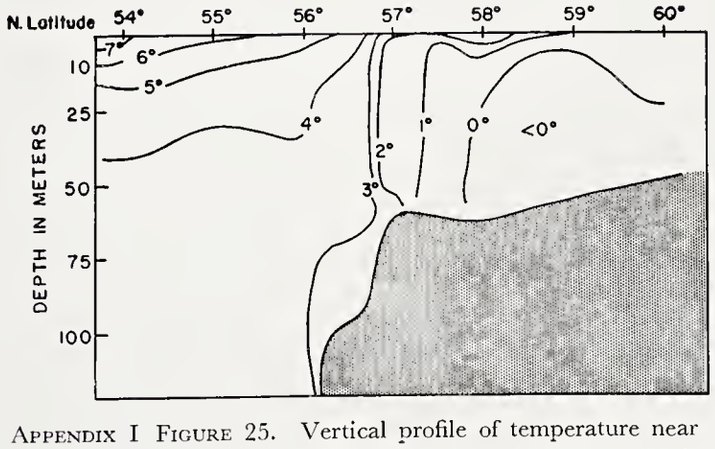
Appendix I Figure 22. Bottom salinity, July–August 1940.



Appendix I Figure 23. Bottom sigma-t, July–August 1940.



Appendix I Figure 24. Vertical profiles of properties near the edge of the continental shelf, June 1958. (Shelf indicated by stippling.)



Appendix I Figure 25. Vertical profile of temperature near the edge of the continental shelf at 170°W., June 1956. (Shelf indicated by stippling.)

APPENDIX II: REVIEW OF OCEANOGRAPHY OF THE WATERS NEAR THE WEST COAST OF VANCOUVER ISLAND, BRITISH COLUMBIA

Lane (1962a, b) has recently reported on the oceanography of the waters off the west coast of British Columbia. The following is a brief review of these studies.

Beginning with a study of Nootka Sound in 1933 (Tully, 1937) Canadian oceanographers have carried out investigations in the coastal areas. Many of these were localized studies, while others attempted to define and describe the more general distributions in the coastal waters.

The local studies include those in Nootka Sound (1933); Barkley Sound (1937, 1950, 1953); the approaches to Juan de Fuca Strait (1937, 1938); Dixon Entrance (1938); the Swiftsure area (1938); and in the area about La Perouse Bank (1960). These areas are identified in Appendix II Figure 1.

Those cruises operating in a more extensive area were the coastal surveys, which covered the shelf area off Vancouver Island (1935, 1936); and off the Queen Charlotte Islands (1935); the offshore survey (1936), which operated seaward from the north, central and southern portions of Vancouver Island; Project Offshore (1950–52), reported by Doe (1955). The more recent cruises are the coastal surveys (1957) which included the area from 46°N. to 56°N. to about 200 miles offshore; the Coastal Seaway cruises (1958, 1959), which monitored several lines of stations seaward of both Vancouver Island and the Queen Charlotte Islands; and the Seaways Program (1960–61) which was a modification of the latter.

The data from all these expeditions have been processed and most of them have been reported (Pacific Oceanographic Group, MS, 1957–60). These reports also include daily seawater observations of temperature and salinity from 21 locations along the British Columbia coast, for varying periods; some since 1933. Recently Tabata (1959) and Hollister (1960) have presented a system of classifying the monthly means of these observations. This classification was undertaken to assist in the work of establishing correlations between fisheries statistics and coastal oceanographic conditions.

Meteorological data are available in the records and publications of the Meteorological Division, Department of Transport. River discharge data are available from records and publications of the Water Resources Division, Department of Northern Affairs and National Resources, Canada, and Water Resources Division, United States Department of the Interior.

Studies of these data have shown that the coastal area is not wholly dominated by oceanic influences, as are most coastal areas in other parts of the world. Instead, the oceanography of the Canadian coastal area is determined by the relative influence of the considerable estuarine discharge and the character of the oceanic waters. A study of the oceanic circulation has shown that off the North American coast the ocean waters separate to form the California Current and the Alaskan Gyre. The area of separation is continually shifting, hence the character of the oceanic water adjacent to the coast varies considerably. The estuarine discharge from the many inlets varies with precipitation and snow storage. In addition, the area is subject to variable winds and strong tides. However, none of these studies were adequate to observe the seasonal sequence of events and to define the mechanisms.

An examination of these data by Lane (1962a) showed that although such features as seaward and vertical gradients, and the coastwise continuity are real, there were considerable variations in short distances and short times which complicate and frequently negate the basic trend. Thus, it was not possible to assume simple continuity between widespread lines of observations, such as seaward from the southern, central and northern ends of Vancouver Island, nor was it reasonable to assume more than a first order consistency of structure. In addition, short term variations were as great or greater than the seasonal or yearly variations.

In a second paper Lane (1962 b) concentrated attention on the considerable data from a local area and assessed the variability and its relation to causative factors (insolation, wind, precipitation, and tides). The area in which sufficient data were available was that seaward of Amphitrite Point (App. II Fig. 2). It is also the widest expanse of the coastal area. He subdivided this area into three belts—each belt having some distinct oceanographic features of structure. The positions of these belts (Inshore, Shelf and Slope) are shown in Appendix II Figure 2. In these belts he was able to deduce a model of temperature and salinity structure and related the major oceanographic features of the model to tides and meteorological elements. It is considered that these ideas, when amplified and extended will lead to a reasonable understanding of the coastal phenomena. At the moment

this description entails much simplification. It is briefly discussed.

The model defines the annual sequence of temperature and salinity structure in five seasonal stages (App. II Fig. 3 to 7) where the letters define the water masses:

	Oceanic	Coastal
Upper Zone	OU	CU
Halocline	OH	CH
Lower Zone	OL	CL

Stage 1 (App. II Fig. 3), from December through March, is in general a period of strong southeast winds, minimum insolation, maximum cooling and runoff. The latter, in this case, is a result of local precipitation as distinct from that in the spring which is associated with mainland rivers and the spring thaw of high regions of ice and snow. The strong southeast winds lead to a condition of convergence and vertical mixing. These associated with cooling lead to a relatively narrow northward flow of cool, well-mixed and brackish water along the coast.

Stage 2 (App. II Fig. 4), through March and April, is largely a period of variable winds, increasing insolation and decreasing runoff. The convergence mechanism relaxes and the brackish water tends to spread seaward. This condition attains fulfillment in Stage 3 (App. II Fig. 5), the period May through July. Also at this time, the mainland rivers are in freshet and tidal action conduces to the formation of large pools of brackish water. Because of these pools, there are marked short term variations in the near-surface waters.

Stage 4 (App. II Fig. 6), from July through October, occurs during the prevalence of weak northwest winds and minimal fresh-water discharge from the land. A weak divergence condition may enhance the spread of brackish water seaward. On the other hand, persistent northwest winds will produce a strong divergence condition, in which case there is not only a spread of brackish water seaward but also a replenishment of these waters from depth, resulting in a breakdown of the new coastal structure and the appearance of relatively cold saline waters. Such conditions have been observed but are not necessarily the persistent characteristics of the area.

Stage 5 (App. II Fig. 7), from October through December, is a time of increasing southeast winds and precipitation. During this stage the oceanic upper zone (OU) deepens. This results in an intensification of the top of the oceanic halocline (OH). Its base descends due to the advent of convergence.

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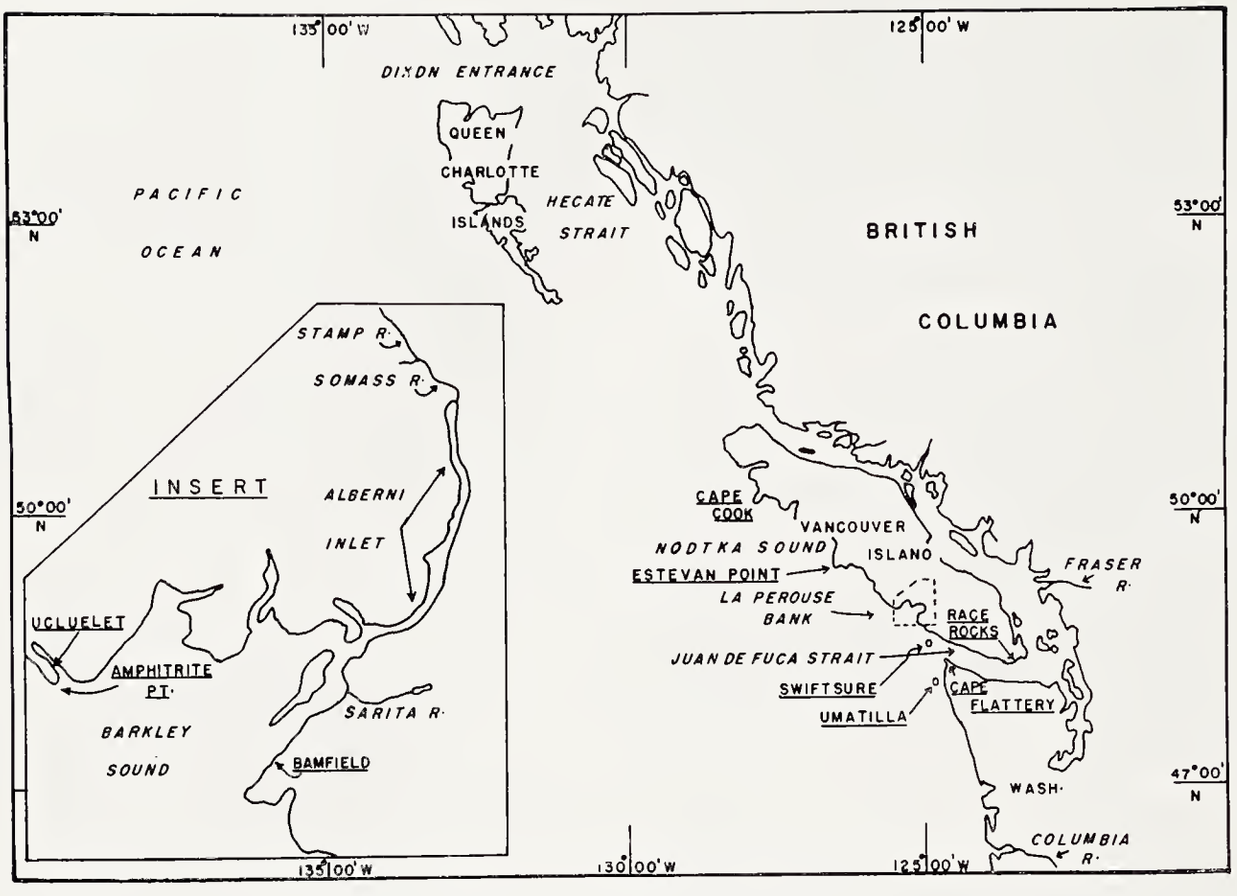
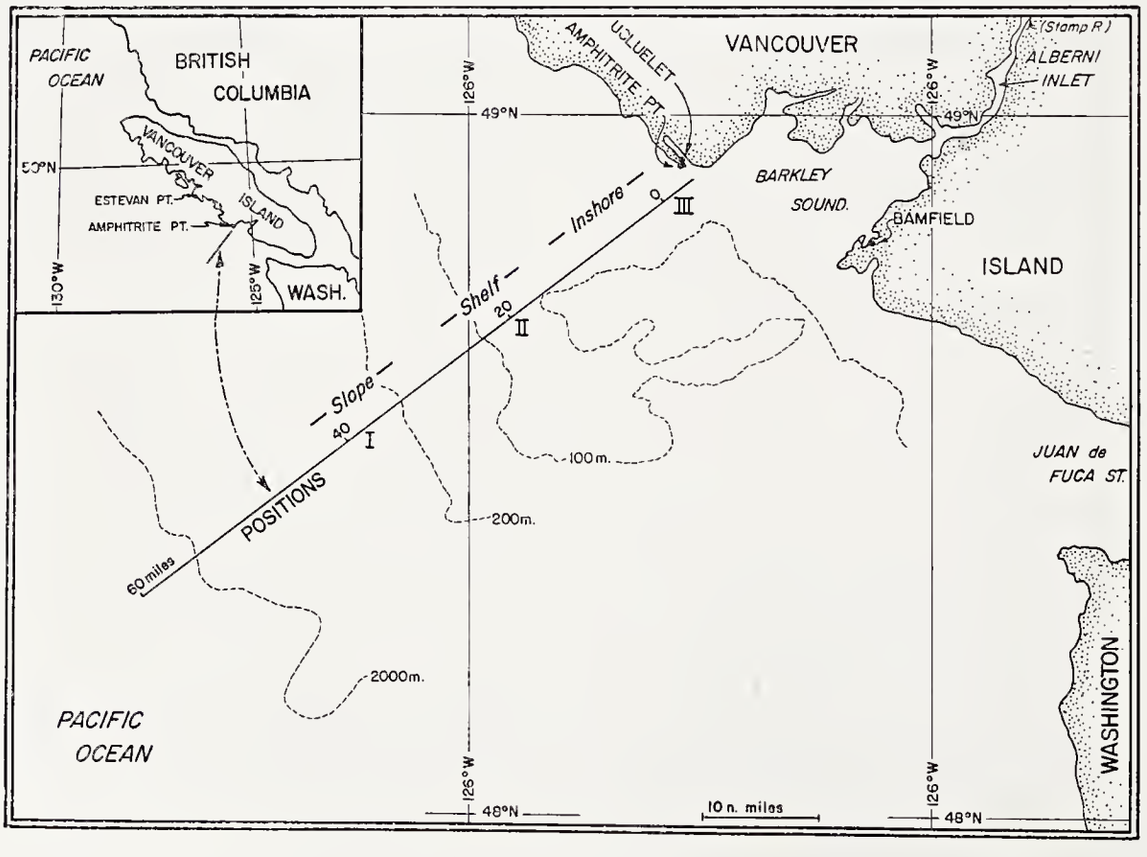
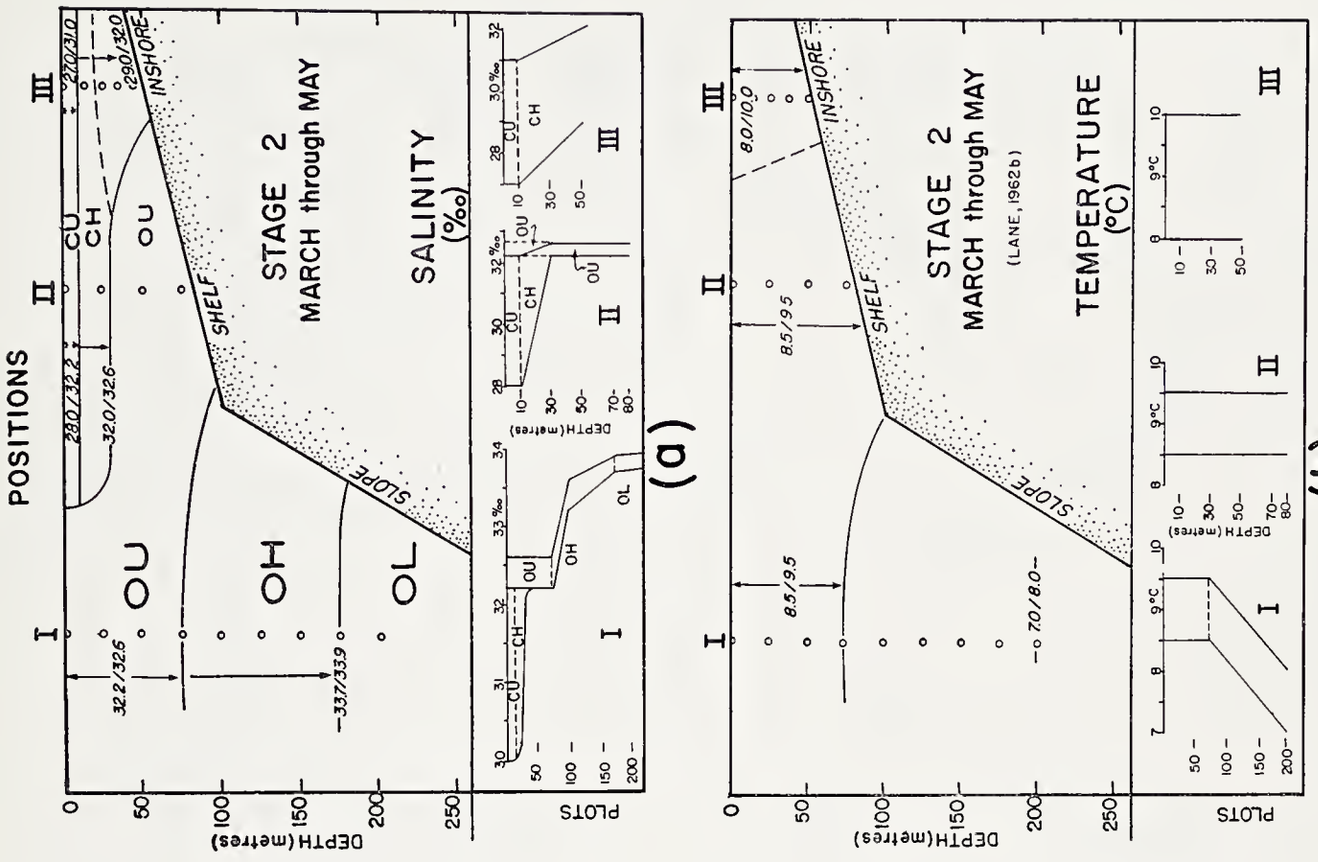


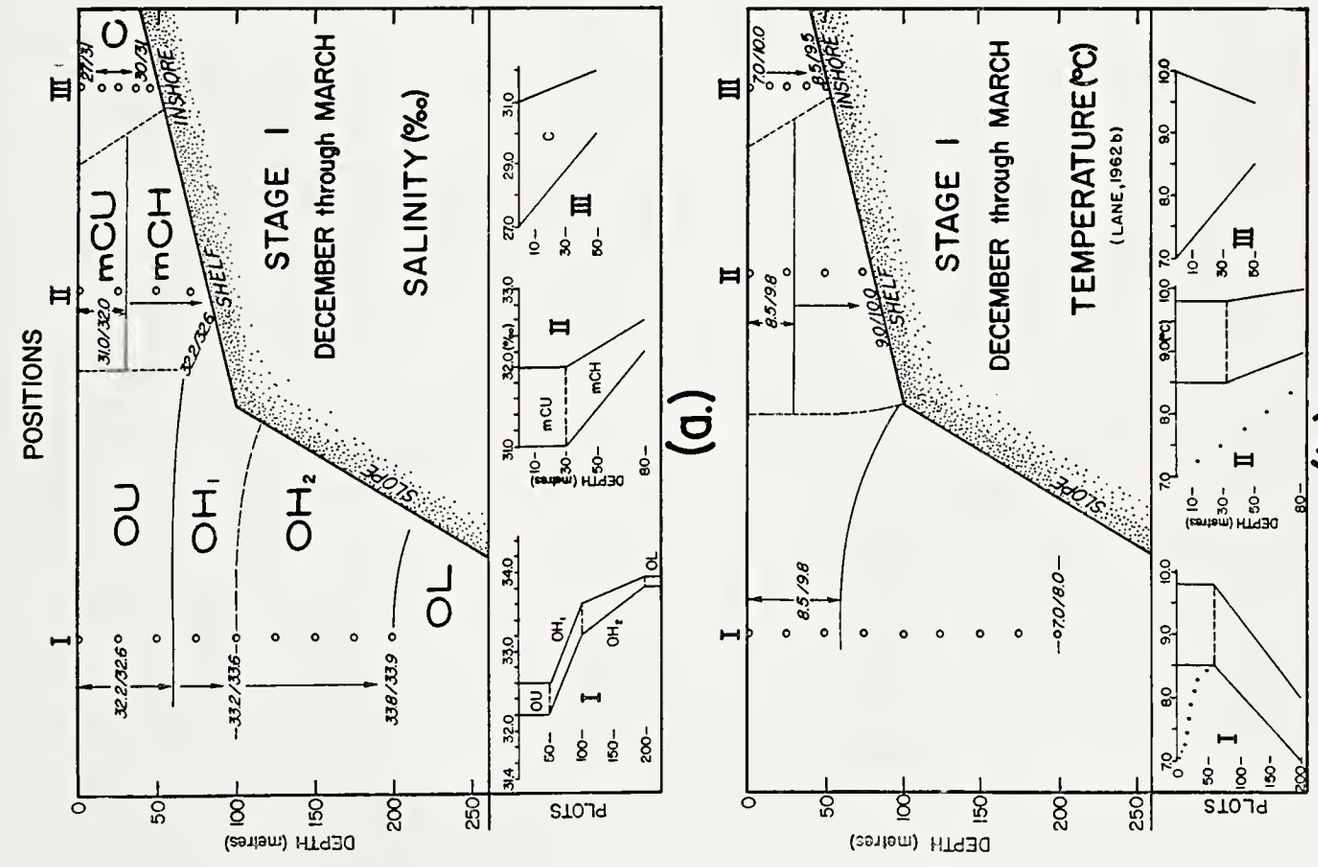
Appendix II Figure 1.



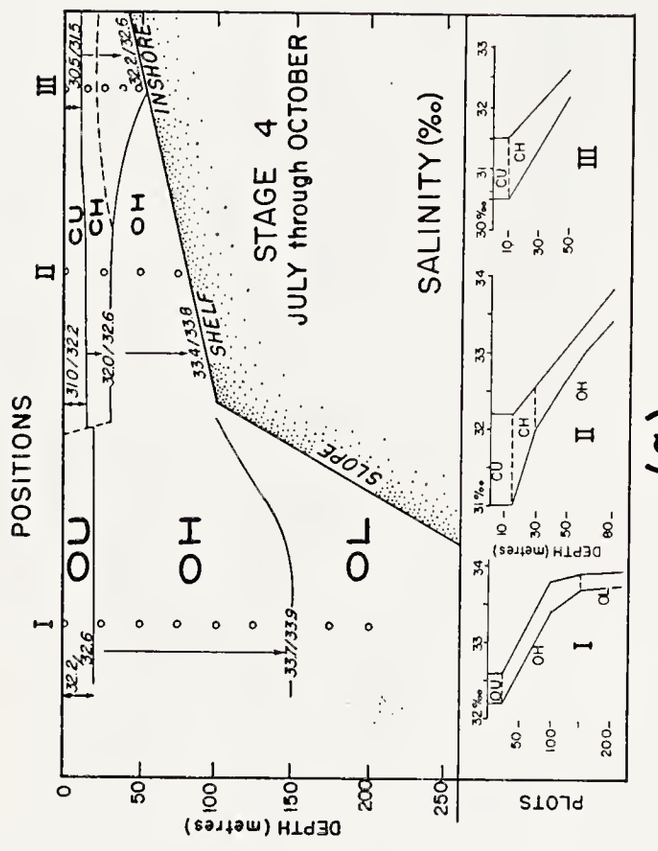
Appendix II Figure 2.



APPENDIX II FIGURE 4.



APPENDIX II FIGURE 3.



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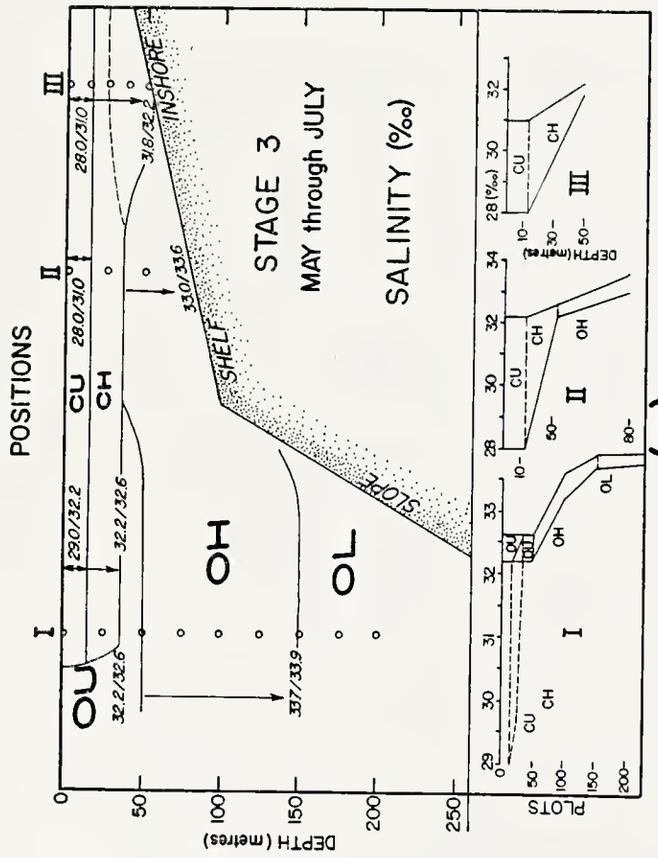
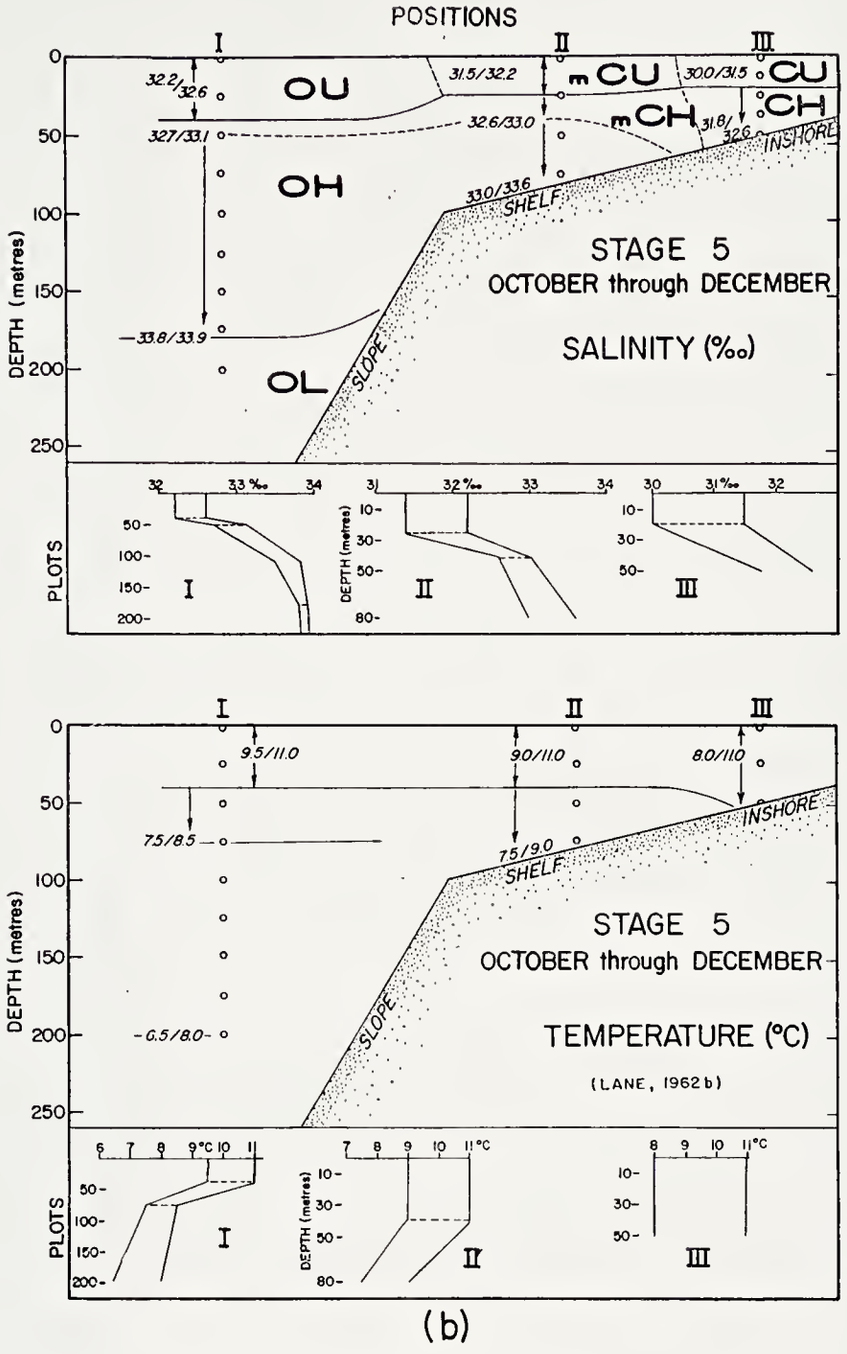


Appendix II Figure 5.



(b)

Appendix II Figure 7.

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